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# AGARD

ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

7 RUE ANCELLE 92200 NEUILLY SUR SEINE FRANCE

**AGARDograph 321**

# On-line Handling of Air Traffic

(Conduite en Ligne du Trafic Aérien)

## Management – Guidance – Control

(Gestion – Guidage – Pilotage)



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# On-line Handling of Air Traffic

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## Management – Guidance – Control)

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by


**A. Benoît, C. Garcia-Avello, J. Lemaître, M. Pélegrin, E. Petre** and **S. Swierstra**

edited by

**André Benoît,** Programme Director


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# Preface

It is quite evident that, if traffic increases as it is expected to, Air Traffic Management concepts which are used at present should soon become obsolete. Full automation is not feasible today. Nevertheless it is conceivable and research - studies and experiments - has been undertaken in this direction[1] .

These points were recognized many years ago. In addition, the fact that political boundaries existed, preventing the integration of control over an extended area covering several States, led to the development of the Zone of Convergence concepts, realizing the integration of en-route and approach control over a region including essentially a main terminal manoeuvering area, TMA, and possibly several secondary airports, and extending anisotropically as far as possible - e.g. 100 nm or even up to 300 nm - away from the converging or critical point, e.g. the runways system centre point.

Presently, several systems aiming at a local efficient management of arrival flights are in operation, in implementation and/or in further development. A critical survey of such systems has been made recently[2], and it is clear that the present trends confirm the adequacy of the above first step undertaken to provide the human controller with advisories generated automatically by the computer.

The next step is clearly the integration of control over a series of such Zones of Convergence or extended terminal manoeuvering areas. To illustrate what is meant, consider a region including several major terminals such as Amsterdam, Brussels, Frankfurt, London and Paris, and the area around each terminal as in the Zone of Convergence concept, now schematized by as many circles whose radii extend as appropriate, to 150 - 250 nm. The total area encircled in this example constitutes a major part of Western Europe.

Clearly, the traffic seen and to be controlled on-line in such a total area includes flights conducted entirely inside this area (regional and Western European traffic), flights originating or terminating outside the area (connecting with the rest of the world) and flights whose origin and destination are both located outside (over-flights). Different sets of control variables apply to each of these different categories of traffic. For instance, initial conditions are imposed for the traffic originating outside, while departure time sequences could be included among them - within reasonable ranges depending on the efficiency of pre-organization units - for the traffic originating inside, whatever the internal or external destinations.

How should we approach the on-line control of the entire traffic in such an extended area in conformity with the numerous and varied severe demands covering, in particular :

- increase of air transport both in volume and diversity;
- conservation of natural resources and deference to the environment;
- national/international economy restrictions;
- general and specific airspace users' requirements.

A main distinction is made between the efforts conducted by all Administrations and Institutions concerned with developing the off-line aspects characterized by different timescales, on the one hand, and the on-line conduct or management of the traffic, including the guidance of each individual flight, on the other hand. The work covered in the off-line category includes special programmes on the increase - or improved use - of capacity (such as construction of additional runways, simultaneous use of parallel runways, reduction, even temporarily, of restricted areas, air traffic flow management), and, in particular, the main project undertaken by the European Organisation for the Safety of Air Navigation, EUROCONTROL, in conjunction with the European Civil Aviation Conference, ECAC, namely the European Air Traffic Control Harmonization and Integration Programme, EATCHIP[3].

[1] *"Towards a Global Air Traffic Management System", G. Maignan. Keynote Address, AGARD Guidance and Control Panel 56th Symposium, 11-14 May 1993, Berlin, Germany.*

[2] *"Time Based Air Traffic Control in an Extended Terminal Area - A survey of such systems", E. Petre. Doc. EUROCONTROL 912009, June 1991.*

[3] *"The EUROCONTROL / ECAC view. The EATCHIP programme", W. Philipp. Paper presented at the International Forum: Congestion in the Skies: The Challenges for the 21st Century, 27-28 January 1994, Paris, France.*

The on-line control of air traffic - globally optimized - over such an area, including several major TMAs, follows and should exploit the results of the previous efforts, the last step having been achieved by the prediction of traffic prepared by a Central Flow Management Unit. Without efficient on-line traffic management and control of individual aircraft, the capital which should result from the preceding developments might be appreciably reduced, if not completely lost.

Accordingly, laying down a programme to specify the characteristics of the on-line component of traffic management and guidance of individual flights in the future European environment has become a necessity. This concern does not really constitute a new idea. The subject was presented and discussed at several workshops or seminars[4]. Even if in many respects, it remains a medium to long term objective, it is nevertheless essential to identify the processes which will require the application or development of mathematical methods or algorithmic techniques. These are, a priori, complex due to the stochastic character of the phenomena themselves and the amount of data to be processed on-line - thus in real time - at a high repetition rate.

Except for the airspace users' operational requirements, the essential demands mentioned above - environment, national resources, developments versus economy restrictions - will appear fairly well defined within perfectly quantified constraints.

There still remain the airline demands and the overall economy requirements of the Community - in a widely acceptable sense as outlined below. As a consequence, the on-line control problem becomes more precise and can be stated in applied mathematical terms. For each aircraft entering the area concerned, this amounts to defining the relevant 4-D trajectory and possibly amending the trajectories of a series of aircraft already flying in the same area.

The relevant determination of the trajectories of all aircraft involved amounts to a complex optimization problem whose essential characteristics include :

- definition of multi-criteria, based essentially on flight economy, i.e. combining cost, time and consumption of all flights concerned. Indeed, it can be shown that the minimum general cost, in case of saturation, tends to correspond to a maximum use of the available capacity;
- accurate specification of the control variables, such as sequences of arrival times for all aircraft with destinations in the controlled area, possible sequences of departure times for all flights originating in the controlled area, and for all aircraft, speed profile control in the vertical plane with some possible adjustments in the horizontal one;
- taking account of all the constraints placed on the system by all additional demands (geographic restrictions, noise abatement procedures, etc.);
- operation on-line - thus in real time - with machine/machine, human/machine and human/human interactions.

The problem is highly complex: it covers a large scale system; it is non-linear, discreet and discontinuous ; as already said, it is stochastic on a very short term basis and involves a set of voluminous data bases, some to be consulted on-line at a high frequency rate. The advisories generated by the computer should be adaptable to the technology available - for instance, Radio-Telephone or Data-Link communications environments - and easily understood by the human controller who will remain sovereign in the control loop. It is to be noted that the computer/controller/pilot interface presently developed in the ZOC/DMA system is directly applicable and has proved to be fully compatible with present and a fortiori future aircraft operation, as shown by the results from a substantial series of tests conducted to date[5] [6].

[4] *"On-line Management and Control of Air Traffic", A. Benoît.*
*"Flow Control of Congested Networks", NATO ASI Series,*
*Series F, Vol. 38, Springer-Verlag, Berlin, Heidelberg 1987. Also Doc. EUROCONTROL 872005, April 1987.*

[5] *"The Air Traffic Controller Facing Automation : Conflict or Co-Operation",*
*A. Benoît , S. Swierstra and R. De Wispelaere.*
*Paper presented at the Conference D3 - Data Dissemination and Display, NAV 87, Royal Institute of Navigation, London, United Kingdom, 29, 30 September - 1 October 1987. Also Doc. EUROCONTROL 872008, July 1987.*

[6] *"A report on flight trials to demonstrate a Mode S data-link in an ATS environment",*
*M. E. Cox, S. Swierstra et al.*
*EUROCONTROL-CAA Mode S Data Link, October 1991.*

At the present stage of the European ATC/ATM development, it should be possible to proceed with such an integration of air traffic handling - with on-line management and control, departure and arrival sequences as essential parts of the control variables - and it is now opportune to initiate the basic developments required to meet such a stimulating challenge.

The initial purpose of this presentation was to outline the general environment in which should be made the selection, assessment and running - in real time - of optimization techniques suitable for conducting on-line an efficient global and optimized management of air traffic over Western Europe.

The criteria of the system should cover overall flight economy and maximum use of available capacity, en-route and in TMAs. Control variables should include individual aircraft flight profiles in both vertical and horizontal planes and, whenever appropriate, times of arrival and, ultimately, times of departure within acceptable limits. The numerous, varied and sometimes contradictory constraints expressed by the various communities involved should be treated in a flexible manner.

The optimization methods presently available to approach such a problem are essentially based on numerical techniques - branch-and-bound, genetic algorithms, for instance - and relatively complex to implement in the on-line ATC/ATM environment. Nevertheless, they should be considered even it is felt that they may be successfully replaced by rather simple strategies as introduced previously in the optimized management of traffic in the Zone of Convergence approach[7].

It is clear that such a work programme calls for competencies not necessarily available in present Air Traffic Services institutions. Already - see the EATCHIP programme, for instance - the increase in complexity of air traffic handling calls for an increase in staff, with members specialized in a variety of disciplines. As a result, young colleagues joining Air Traffic Control advanced project teams may be highly competent in their specific field, be it information theory, optimization techniques, automated data communications etc., but, at the same time lacking a basic knowledge of the Air Traffic Control background and the associated constraints.

For those new to the Air Traffic Control Research and Development community, this AGARDograph should offer, on the one hand, a precise idea of a particular long term system objective and, on the other hand, a broad view of the present situation and actual limitations.

After a **General Introduction** and a short note on **The Air Transport System** (Chapter 1), some aspects of the **Air Traffic Complexity** is presented (Chapter 2). The trends of the **Traffic Evolution** are then outlined (Chapter 3), this presentation being based essentially on the information published regularly by the International Civil Aviation Organization (ICAO).

In line with the educational textbook character of this AGARDograph, Chapter 4 is devoted to the **Electronic Aids to Controllers** presently available at the control center. Chapter 4 constitutes an introduction to the subject, it summarizes the essential technological supports currently available, while the aids to assist the human controller at the decision making level as presently developed at the Engineering Directorate[8] of the European Organisation for the Safety of Air Navigation are described in a separate and subsequent section, entitled **Decision Making Aids** (Chapter 6).

Besides Conflict Alert - also referred to as Safety Net - systems, the first steps undertaken to develop aids were related to the terminal area extended to cover an appreciably wider area than the current - or in some places, the former - 25 nm extent. A substantial coverage of the subject, including a critical review of the systems developed, is made under the title "**Arrivals Management Systems**" (Chapter 5).

From where we stand today, it is worth to dare "**A Look Further into the Future**" (Chapter 7). Some 20 years ago, the Federal Aviation Administration had already initiated a programme of work aiming at automating if only partly, most of the en-route filed regular traffic. It appeared to us that such a programme was never perceived as fully realistic, partly due to some lack of understanding between the developers and the potential users. In terms of automation, the conduct of air traffic control constitutes a complex large scale system; its full automation remains a great challenge (See Note[1], page iii) and it will not be treated here. Instead, we shall limit this presentation to an outline of two transitional steps, one extending from the on-line management of arrival traffic, the other applying simultaneously to a series of main terminals as suggested at the beginning of this

[7] *"Air Traffic Handling and Ground-Based Guidance of Aircraft",*
*AGARDograph N° 301, "Aircraft Trajectories : Computation - Prediction - Control",*
*Vol. II, AGARD, Neuilly-sur-Seine, France, May 1990.*

[8] *Now the Directorate of Eatchip Development.*

Preface. Then, in chapter 8, some emphasis is placed on several general aspects of this last approach, under the title **Towards Global Optimization.**

The initial assessment and, subsequently, the thorough validation of advanced on-line ATM concepts implying an accurate 4-D control of each aircraft trajectory, require simulation facilities suitable to reproduce in particular, the behaviour of the pilot/aircraft system in a highly realistic manner. It appeared that classic experimental units did not contain such resources. Accordingly, complementary facilities were developed to supply the lacking components, an example of which is presented in chapter 9 under the title **Systems Evaluation Facilities**.

The advanced ATM concepts rarely integrate the ground movements from gate to brake-release and from touch-down to gate. The reason is simply the complexity of the entire system. At some future stage, these components should nevertheless be integrated in a global management system. The last chapter of this book suggests some guidelines to look at the **The Airport of the Future** (Chapter 10). This important subject will be treated further in an open forum[9] and it is hoped that precise practical recommendations will result.

In concluding this foreword, we wish to welcome the young graduates joining this fascinating field known historically as Air Traffic Control and fully open to innovation, science application and technological development.

André Benoît
Programme Director
Guidance and Control Panel

[9] *Académie Nationale de l'Air et de l'Espace, ANAE, Toulouse, France, Programme d'activités 1995.*

# Préface

Si la circulation aérienne continue de croître comme le prévoient les spécialistes de l'évolution de la société, les concepts de gestion des mouvements aériens actuellement employés seront rapidement dépassés. Une automatisation complète du contrôle de la circulation aérienne n'est pas réalisable aujourd'hui. Néanmoins, elle est concevable: études et expérimentations ont été entreprises dans cette voie[1].

Le caractère critique de la situation actuelle est reconnu depuis de nombreuses années. Une approche globale est difficile. L'existence de frontières politiques qui empêchaient l'intégration du contrôle sur une zone élargie couvrant plusieurs Etats a conduit au développement de concepts du type de Zone de Convergence. Ces concepts réalisent l'intégration du contrôle en route et du contrôle d'approche sur une région comprenant essentiellement une aire de manoeuvre terminale TMA, avec, éventuellement, des aéroports secondaires, et s'étendant de façon anisotropique aussi loin que possible (soit sur 100 voire 300 nautiques) de points de convergence ou critiques, par exemple, le point central d'un réseau de pistes.

Actuellement, différents systèmes d'assistance automatisée visant une gestion locale efficace des vols à l'arrivée sont déjà en service, d'autres sont en cours d'implantation - de développement avancé. Un examen critique de tels systèmes a été effectué récemment[2]. Les tendances actuelles confirment l'adéquation de ces premières mesures développées pour fournir aux contrôleurs humains une aide générée automatiquement par l'ordinateur.

L'étape suivante est évidemment l'extension d'un contrôle intégré à un ensemble de telles zones de convergence ou aires d'approche terminales étendues. Pour illustrer ce point, considérons une région comprenant plusieurs terminales importantes, soit l'ensemble Amsterdam, Bruxelles, Francfort, Londres et Paris, ainsi que la zone de convergence associée à chacun de ces aéroports, schématisée dans ce cas par autant de cercles dont les rayons s'étendent, selon le cas, à 150 - 250 nautiques. Dans cet exemple, la superficie totale ainsi encerclée constitue une partie importante de l'Europe occidentale.

Le trafic à contrôler en-ligne dans une telle zone se compose de vols entièrement accomplis à l'intérieur de la zone (trafic régional et occidental), de vols qui débutent ou se terminent en dehors de la zone (en transit vers le reste du monde) et de vols pour lesquels le point de départ et le point d'arrivée sont tous deux en dehors de la zone (survols). A chacune de ces catégories de trafic correspondent des ensembles de variables de contrôle différents. Par exemple, les conditions initiales sont imposées pour le trafic venant de l'extérieur tandis que les séquences des temps de décollage pourraient ou devraient être incluses parmi les variables de contrôle des vols d'origine interne - moyennant une marge de contrôle appropriée à l'efficacité de gestion préalable des flux de trafic - quelles que soient leurs destinations internes ou externes.

Comment envisager le contrôle en-ligne de l'ensemble du trafic dans une telle zone étendue, compte tenu de la diversité des exigences nombreuses et sévères portant en particulier sur :

- l'évolution du volume et de la diversité des transports aériens,
- la conservation des ressources naturelles et le respect de l'environnement,
- les éventuelles restrictions économiques nationales et internationales,
- les besoins généraux et spécifiques des utilisateurs de l'espace aérien.

Une distinction essentielle doit être faite entre les efforts entrepris par les administrations et organismes qui développent les aspects hors-ligne - d'ailleurs caractérisés par différentes échelles de temps -, d'une part, et la conduite ou la gestion en-ligne du trafic comprenant le guidage individuel de chaque vol, d'autre part. Le travail couvert par la catégorie hors-ligne comprend des programmes particuliers sur l'accroissement - ou la meilleure utilisation - de la capacité (par exemple, la construction de pistes supplémentaires, l'utilisation simultanée de pistes parallèles, la réduction, même à titre provisoire, des zones réglementées, la régulation de la circulation aérienne), et, en particulier, un projet principal entrepris conjointement par EUROCONTROL, l'Organisation Européenne

[1] *"Towards a Global Air Traffic Management System", G. Maignan. Keynote Address, AGARD Guidance and Control Panel 56th Symposium, 11-14 May 1993, Berlin, Germany.*

[2] *"Time Based Air Traffic Control in an Extended Terminal Area - A survey of such systems", E. Petre. Doc. EUROCONTROL 912009, June 1991. (Voir Chapitre 5).*

pour la Sécurité de la Navigation Aérienne et la CEAC, la Conférence Européenne de l'Aviation Civile, à savoir, le programme Européen d'Harmonisation et d'Intégration du Contrôle de la Circulation Aérienne, EATCHIP[3].

Le contrôle en-ligne de la circulation aérienne - optimisé globalement - sur une telle zone, comprenant plusieurs grandes aires de manoeuvre terminales TMA, s'ensuit et devrait exploiter les résultats des efforts précédents, la dernière contribution résultant des prévisions de trafic établies par la cellule centrale de régulation. Sans une gestion en-ligne efficace du trafic, associée au guidage individuel et au pilotage des appareils, le bénéfice qui devrait résulter des développements précédents risque d'être considérablement diminué, sinon perdu à jamais.

En conséquence, l'établissement d'un programme pour la spécification des caractéristiques du composant en-ligne de la gestion des mouvements aériens et du guidage individuel des vols dans le contexte de l'Europe de demain devient une nécessité. Toutefois, cette préoccupation n'est pas vraiment nouvelle. Le sujet a déjà été présenté et discuté dans divers ateliers et congrès[4]. Même si, à bien des égards, un tel programme représente un objectif à moyen ou à long terme, il est néanmoins indispensable d'identifier les processus qui exigeront l'application voire le développement de méthodes mathématiques ou de techniques algorithmiques. Ces méthodes et techniques sont a priori complexes, ne fût-ce qu'en raison du caractère stochastique des phénomènes eux-mêmes et du volume important des données à traiter en-ligne, donc en temps réel, à une fréquence de récurrence élevée.

Les besoins opérationnels des utilisateurs de l'espace aérien mis à part, les exigences essentielles citées ci-dessus - l'environnement, les ressources nationales, les développements par rapport aux restrictions économiques - semblent être relativement bien définies dans un cadre de contraintes bien quantifiées.

Restent les besoins des compagnies aériennes et les exigences de l'économie globale de la communauté - au sens large - tels qu'exposés dans leurs grandes lignes ci-dessous. En conséquence le problème du contrôle en-ligne se précise et peut être exprimé en termes mathématiques. Pour chaque appareil qui pénètre dans la zone concernée, ceci revient à redéfinir la trajectoire 4D appropriée et peut-être à corriger les trajectoires d'un certain nombre d'avions évoluant à l'intérieur de la même zone.

La détermination des trajectoires de tous les avions concernés représente un problème d'optimisation complexe dont les caractéristiques essentielles comprennent :

- la définition de multi-critères, basés essentiellement sur la notion d'économie, c'est-à-dire la combinaison des facteurs coût, temps et consommation de carburant pour l'ensemble des vols concernés. Il peut en effet être démontré qu'en cas de saturation le coût global minimum tend à correspondre à l'utilisation maximale de la capacité disponible;

- la spécification précise des variables de contrôle, telles que les séquences des temps d'arrivée (pour tous les avions dont la destination se trouverait à l'intérieur de la zone contrôlée), les séquences d'heures de départ (pour tous les vols partant de la zone contrôlée) et (pour tous les avions) les profils de vitesse dans le plan vertical avec d'éventuels ajustements dans le plan horizontal;

- la prise en compte de l'ensemble des contraintes imposées au système pour toutes les demandes supplémentaires (restrictions géographiques, procédures d'exploitation à moindre bruit, etc.);

- l'exploitation en-ligne, donc en temps réel, avec interaction machine/machine, homme/machine et homme/homme.

Le problème est extrêmement complexe : il concerne un système à grande échelle; il est non linéaire, discret et forcément discontinu; comme il est dit plus haut, il est stochastique dans le très court terme et fait appel à des bases de données volumineuses, dont certaines doivent être consultées en-ligne à des intervalles très rapprochés. Les conseils ou directives élaborés par l'ordinateur doivent être compatibles avec les technologies disponibles, par exemple la radiotéléphonie ou les systèmes de télécommunications numériques automatiques, et aisés à

[3] *"The EUROCONTROL / ECAC view. The EATCHIP programme", W. Philipp.
Paper presented at the International Forum: Congestion in the Skies:
The Challenges for the 21st Century, 27-28 January 1994, Paris, France.*

[4] *"On-line Management and Control of Air Traffic", A. Benoît.
"Flow Control of Congested Networks", NATO ASI Series,
Series F, Vol. 38, Springer-Verlag, Berlin, Heidelberg 1987. Also Doc. EUROCONTROL 872005, April 1987.*

interpréter par le contrôleur humain qui - pour une longue période encore - demeurera souverain dans la boucle de contrôle. Il est à noter que l'interface ordinateur/contrôleur/pilote telle que développée pour le système ZOC/DMA est directement applicable et s'est avérée compatible avec les procédures actuelles d'exploitation et a fortiori avec celles prévues à l'avenir, conclusion résultant des nombreuses campagnes d'essais effectuées jusqu'à ce jour[5] [6].

Au stade actuel du développement européen de l'ATC/ATM, il doit être possible de procéder à une telle intégration, avec gestion et contrôle en-ligne incluant les séquences d'arrivée et de départ comme éléments essentiels des variables de contrôle. Il s'agit désormais d'initier les développements de base destinés à relever ce défi.

L'objet initial de cette présentation était de tracer les grandes lignes des conditions générales souhaitables en ce qui concerne le choix, l'évaluation et l'exploitation, en temps réel, des techniques d'optimisation adaptées à la conduite en-ligne d'une gestion globale, optimisée et efficace des mouvements aériens sur l'Europe occidentale.

Les critères retenus dans le cas d'un tel système doivent refléter l'économie globale des vols et l'utilisation maximale de la capacité disponible en route et en zone TMA. Les variables de contrôle doivent inclure les profils de vol individuels dans les plans verticaux et horizontaux, et, selon le cas, les temps d'arrivée et de départ dans des limites acceptables. Il doit être tenu compte, de manière souple, des contraintes nombreuses, diverses et parfois contradictoires exprimées par les différentes communautés impliquées dans le projet.

Les méthodes d'optimisation disponibles actuellement pour aborder un tel problème sont essentiellement basées sur des techniques numériques, par exemple séparation-évaluation, algorithmes génétiques, etc. Elles sont aussi relativement complexes à mettre en oeuvre dans le contexte ATC/ATM en-ligne. Néanmoins, elles doivent être prises en considération, même s'il y a lieu de penser qu'elles pourraient être remplacées par des stratégies plutôt simples, comme celles déjà utilisées pour l'optimisation de la gestion des mouvements aériens dans la technique dite Zone de Convergence[7].

Un tel programme de travail exige des compétences qui ne sont pas nécessairement disponibles au niveau des services de la circulation aérienne. Déjà aujourd'hui, dans le cas du programme EATCHIP par exemple, la complexité accrue des opérations d'acheminement du trafic nécessite l'augmentation du personnel et l'inclusion dans les équipes existantes, de spécialistes hautement qualifiés dans diverses disciplines de pointe. Par conséquent, il se peut que de jeunes collègues entrant dans les équipes de projets avancés du service du contrôle de la circulation aérienne soient particulièrement compétents dans leurs spécialités, que ce soit la théorie de l'information, les techniques d'optimisation, la télématique etc. mais n'aient qu'une connaissance élémentaire du contrôle de la circulation aérienne et des contraintes y associées.

Pour ceux qui découvrent la communauté de recherche et développement du Contrôle de la Circulation Aérienne, cette AGARDographie devrait donner d'une part, un aperçu de la situation et des limitations actuelles et d'autre part une idée précise d'un objectif-système à long terme.

Après une **Introduction Générale** et une esquise du **Système de transport aérien** (Chapitre 1), la **Complexité du trafic aérien** est illustrée au chapitre 2. Les tendances de **l'Évolution du trafic** sont esquissées au chapitre 3, cette présentation étant basée sur les informations publiées régulièrement par l'Organisation de l'Aviation Civile Internationale (OACI).

[5] *"The Air Traffic Controller Facing Automation : Conflict or Co-Operation", A. Benoît , S. Swierstra and R. De Wispelaere. Paper presented at the Conference D3 - Data Dissemination and Display, NAV 87, Royal Institute of Navigation,London, United Kingdom, 29, 30 September - 1 October 1987. Also Doc. EUROCONTROL 872008, July 1987.*

[6] *"A report on flight trials to demonstrate a Mode S data-link in an ATS environment", M. E. Cox, S. Swierstra et al. EUROCONTROL-CAA Mode S Data Link, October 1991.*

[7] *"Air Traffic Handling and Ground-Based Guidance of Aircraft", AGARDograph N° 301, "Aircraft Trajectories : Computation - Prediction - Control", A. Benoît (Editor) Vol. II, AGARD, Neuilly-sur-Seine, France, May 1990.*

En conformité avec le caractère éducatif de cette AGARDographie, le chapitre 4 constitue une introduction aux **Aides électroniques au contrôleur**, telles qu'actuellement disponibles au centre de contrôle, tandis que les outils susceptibles d'apporter une aide au contrôleur au niveau décisionnel et actuellement en cours de développement à la Direction technique[8] de l'Organisation Européenne pour la Sécurité de la Navigation Aérienne sont décrits dans un chapitre distinct, intitulé **Aide à la décision** (Chapitre 6).

Mis à part les systèmes d'alarme détectant les infractions aux normes de séparation, les premiers développements de l'aide à la décision portent sur la gestion des vols à l'arrivée dans une zone terminale étendue. Une analyse détaillée des systèmes envisagés ainsi qu'une revue critique de leurs mérites respectifs sont présentées sous le titre **Systèmes de gestion des arrivées** (Chapitre 5).

Au stade actuel, il est tentant de risquer un **Regard sur l'avenir** de la gestion en-ligne du trafic aérien (Chapitre 7). Voici déjà 20 ans, l'Administration américaine (Federal Aviation Administration) avait initié un programme de recherche visant à automatiser, fût-ce partiellement, le contrôle de la plupart du trafic en-route, régulier et pré-enregistré. Il semble - à nos yeux - que le réalisme de ce sujet ne fut jamais bien perçu, peut-être, en partie, par manque de compréhension entre développeurs et utilisateurs potentiels. En termes d'automatisation, la conduite du contrôle de la circulation constitue un grand système extrêmement complexe, comme suggéré antérieurement. L'automatisation complète - le remplacement du contrôleur humain par des matériels et des logiciels - reste un grand défi (voir note[1], page vii) qui n'est pas traité dans cet ouvrage. Seules deux phases de transition sont abordées, l'une intégrant les techniques d'aide à la décision comme une extension de la gestion en-ligne des vols à l'arrivée, l'autre envisageant la gestion en-ligne simultanée d'un ensemble de grandes terminales comme décrit au début de cette préface. Ensuite, le chapitre 8 analyse quelques aspects généraux relatifs à cette dernière approche, sous le titre **Vers une optimisation globale.**

Les essais initiaux et par la suite la validation de concepts conçus et développés pour la gestion en-ligne du trafic aérien impliquent le contrôle quadridimensionnel de chaque vol et nécessitent des unités de simulation susceptibles de reproduire d'une manière très réaliste le comportement du système pilote/avion. Il est apparu très rapidement, que les unités de simulation classiques ne possédaient pas de telles ressources. Aussi, des facilités complémentaires furent-elles conçues, développées et mises en oeuvre pour fournir les composantes manquantes. Sous le titre **Unité d'évaluation de systèmes**, le chapitre 9 présente comme exemple une réalisation originale.

Les développements actuels de concepts de gestion du trafic aérien intègrent rarement les mouvements au sol de la porte de départ au point de lâcher des freins et du point de toucher des roues à la porte d'arrivée. La raison en est simplement la complexité du système complet. Il n'empêche que, à un stade ultérieur de nos développements, ces phases devront être intégrées, elles aussi, dans un système de gestion globale. Le dernier chapitre de cet ouvrage formule quelques suggestions sur la manière d'envisager **l'Aéroport du futur** (Chapitre 10). Notons que ce thème important fera d'autre part l'objet d'un colloque[9] dont pourront résulter, nous l'espérons, des recommandations pratiques précises.

Pour conclure cette préface, nous souhaitons la bienvenue aux jeunes diplômés désireux de joindre leurs efforts à notre communauté et d'exercer leur métier dans cette discipline fascinante qu'est le Contrôle de la Circulation Aérienne, discipline pleinement ouverte aux innovations, applications scientifiques et développements technologiques.

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[8] *Maintenant Direction du Développement EATCHIP.*

[9] *Académie Nationale de l'Air et de l'Espace, ANAE, Toulouse, France, Programme d'activités 1995.*

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# Activities in Air Traffic Handling

Over the past 20 years, the Guidance and Control Panel of the Advisory Group for Aerospace Research and Development to the North Atlantic Treaty Organization has devoted part of its activities to the fascinating field known historically as **Air Traffic Control**.

The Panel's contributions listed below cover in particular, the air and ground components considered as parts of a single system, the methods, techniques and technologies applicable to or usable for the management of the flows of aircraft and the control of individual flights, the integration of control phases over extended areas, the 4-D guidance of aircraft in critical conditions, the ever-increasing level of automation, the introduction of machine intelligence and its impact on the essential role of the human acting on-line in the control loop.

**AIR TRAFFIC CONTROL SYSTEMS**
Guidance and Control Panel Symposium, Edinburgh, Scotland, 26-29 June 1972.
AGARD-CP-105, April 1973.

**A SURVEY OF MODERN AIR TRAFFIC CONTROL**
AGARDograph AG-209, Vols. I and II, July 1975.

**PLANS AND DEVELOPMENTS FOR AIR TRAFFIC SYSTEMS**
Guidance and Control Panel Symposium, Cambridge, Mass., USA, 20-23 May 1975.
AGARD-CP-188, February 1976.

**AIR TRAFFIC MANAGEMENT :**
**Civil/Military Systems and Technologies**
Guidance and Control Panel Symposium, Copenhagen, Denmark, 9-12 October 1979.
AGARD-CP-273, February 1980.

**AIR TRAFFIC CONTROL IN FACE OF**
**USERS' DEMAND AND ECONOMY CONSTRAINTS**
Guidance and Control Symposium, Lisbon, Portugal, 15 October 1982.
AGARD-CP-340, February 1983.

**EFFICIENT CONDUCT OF INDIVIDUAL FLIGHTS AND AIR TRAFFIC** or
**"An Optimum Utilisation of Modern Technology**
(Guidance, control, navigation, surveillance and processing facilities)
**for the Overall Benefit of Civil and Military Airspace Users"**
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AGARD-CP-410, December 1986.

**AIRCRAFT TRAJECTORIES :**
**Computation - Prediction - Control**
AGARDograph AG-301, Vols. I (March 1990), II and III (May 1990) :

Vol. I
- **FUNDAMENTALS**
- **FLIGHT IN CRITICAL ATMOSPHERIC CONDITIONS**
- **IMPACT OF NEW ON-BOARD TECHNOLOGIES ON**
- **AIRCRAFT OPERATION**

Vol. II
- **AIR TRAFFIC HANDLING**
- **GROUND-BASED GUIDANCE OF AIRCRAFT**

Vol. III
- **ABSTRACTS**
- **BIBLIOGRAPHY**
- **CONTRIBUTORS**

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Guidance and Control Panel Symposium, Berlin, Germany, 11-14 May 1993.
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**Management - Guidance - Control**
AGARDograph AG-321, this volume.

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# HANDLING OF AIR TRAFFIC

## General Introduction

## AIR NAVIGATION AIDS
## AIR TRAFFIC CONTROL AIR TRAFFIC MANAGEMENT
## AIR TRAFFIC FLOW MANAGEMENT
## EUROPEAN AIR TRAFFIC MANAGEMENT SYSTEM

by

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## FOREWORD

In 1983, we were invited by the Associazone Elettrotecnica e Elettronica Italiana to deliver a lecture dealing with some particular aspects of "***air traffic management***" in a seminar devoted to "***air navigation aids***"[1]. The terms "air navigation aids" will probably suggest an idea rather clear in the mind of the reader i.e. any facility which permits or facilitates navigation, guidance and possibly air traffic control, this latter in terms of guidance directive generation. By contrast, the expression "air traffic management" which in general covers an adequate organisation of the traffic is rather new and it may require some additional qualification if ambiguities are to be avoided. Accordingly, this general introduction will outline what should currently be understood by these terms as well as their relationship in the context of this general presentation.

## 1. AIR NAVIGATION AIDS

*Air navigation aids include ground-based, self contained and space-based aids [Ref. 1].*

***Ground-based navigation aids***, mostly developed from radio-location concepts, generate radio coordinates usable in the cockpit without reference to the aircraft (compass) heading. They cover short-to-medium and long distance aids.

*Short-to-medium distance aids* include in particular the very high frequency omni-directional radio beacon (VOR), the Doppler-VOR beacon which offers the advantage over the VOR beacon of reducing the site error, and the tactical air navigation system (TACAN) used by the military for short-to-medium range operation. *Long distance aids* include Omega, Loran, Consol and Decca and provide position information through hyperbolic coordinate systems.

In a more general sense, ground-based navigation aids should also include distance measuring equipment - also

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[1] ***"Air Traffic Management : Development of techniques and procedures for the control of individual flights and air traffic in an advanced TMA"****. Lecture delivered by the author at the Seminar on "Air Navigation Aids", Associazone Elettrotecnica e Elettronica Italiana, Milan, Italy, 27 February 1986.*

included in TACAN - landing guidance systems and collision avoidance. *Distance measuring equipment* (DME) provides the aircraft with an accurate estimate of the distance (slant range) to a selected ground station. *Automatic aids for landing* essentially include the instrument landing systems (ILS) in three main versions corresponding to three levels of accuracy and the microwave landing system (MLS) which in principle allows automatic guidance for curved and segmented landing paths.

***Self-contained navigation aids*** include Doppler radar and inertial navigation. Inertial navigation provides the aircraft motion characteristics, translation of the centre of gravity and rotations of the aircraft around it, without reference to a network of ground-based facilities.

The use of ***satellites for navigation*** in civil aviation is becoming a reality. Besides the Global Positioning System currently used by General Aviation, the relevant requirements have been defined by the Special Committee on Future Air Navigation Systems of the International Civil Aviation Organisation [Refs. 2, 3, and more recently Ref. 3a].

## 2. AIR TRAFFIC CONTROL (ATC)

*In a wide sense, Air Traffic Management includes Air Traffic Control.*

Historically, the term ***Air Traffic Control*** relates to actions undertaken by traffic controllers to ensure a safe and expeditious flow of traffic. The ATC controller had and still has a picture of the air traffic situation which is extremely limited in the space-time continuum. Furthermore, tools are lacking to give him a reliable view of the future implications of his actions. Accordingly, he or she obviously takes a conservative attitude : safety is clearly and rightly the controller's primary concern ; delays build up and financial penalties follow. This was the situation already in the early 70s when competent advisers suggested that a broader view of the traffic problems should be available, not necessarily at the controller position level, but at some upstream, preferably centralized, position. In addition, the use of new technologies likely to have potential impact on air traffic control, were to be considered.

## 3. AIR TRAFFIC MANAGEMENT (ATM)

*The expression **Air Traffic Management** then appeared in the literature.*

The expression covered the use of all available resources to lead to an efficient control of air traffic. Subsequently, this terminology became fashionable ; a number of system designations including the new term emerged, initially in the United States and subsequently in Europe.

As a consequence, it may be useful to proceed with a few historical remarks, then summarise what could reasonably be understood by "traffic management" in a general manner. This should be instructive since, in particular, the Concise Oxford dictionary of current English defines the substantive "management" as meaning not only a "***governing body***" but also a "***trickery, deceitful contrivance***".

In 1971, the Federal Aviation Administration of the United States defined two traffic regulation functions, one at the local level, termed "***local flow control***" to deal with short term planning aspects, the other one, at the national level, called "***central flow control***" to handle aspects associated with longer term planning.

The ***Central Flow Control Facility*** is aimed at minimizing the overall fuel consumption subject to a number of constraints including, in particular, the utilisation of the full system capacity. The possible actions which could be taken included (a) holding aircraft on the ground either before departure or at an intermediate airport ; (b) holding aircraft in the air ; (c) using speed control en-route ; (d) changing route of flight.

The ***System Command Centre*** has an appreciable amount of information available to determine, as accurately as possible, the present air traffic demand and the system traffic handling capacity. *To our knowledge,* ***this function constituted the first attempt to regulate the air traffic on-line on a large scale in accordance with general control theory*** (criterion, constraints, control variables).

Although the words were not used, this last regulation function clearly falls within what is now termed "***Air Traffic***

***Management***". The relevant terminology appears slightly later in the literature as described in a subsequent paragraph. Nevertheless, roughly one decade later, on this side of the Atlantic, the terminology "***Air Traffic Flow Management***" was retained to translate predictions - in particular saturation - of the ATC controller's workload into traffic advisories to be relayed upstream, ideally to the centres including the airports of origin. In spite of such a designation suggesting a broad overall view, the differences with the previous U.S. central flow control were appreciable. In particular, the European regulation function was segmented : at any one time, up to 11 cells existed in different countries, each operating in a sovereign manner. Actions undertaken *here and now* might have an adverse effect *somewhere else later on*. This left appreciable congestion; in particular, important delays were still suffered by the traffic to and from the South and South-East of Europe.

The remedy for this situation involved, among other developments, two main undertakings. First, the constitution of a central unit generating control directives in terms of their effect on the whole of the traffic over the European continent. Secondly, adequate collections - and updates - of data to elaborate realistic predictions of the flow of traffic useful to adjust actuals to capacity. This last point was due to become a reality through the Central Data Bank established by the Member States of the European Organisation for the Safety of Air Navigation (EUROCONTROL). It will do so provided that the data available and techniques elaborated make it possible to predict accurately the future position of each aircraft of the fleets concerned. In Europe, the ***Central Flow Management Unit*** (CFMU) established by the same Organisation, should and will now play a leading role in this field, ensuring an adequate distribution of the demand throughout the evolving capacity availability.

## 4. OPTIMUM CONDUCT OF AIR TRAFFIC

Without conducting a thorough ***biographical search*** to establish the first use of the term "***air traffic management***" as meaning ***an efficient use of resources to perform an optimum conduct of air traffic***, we could reasonably say that this terminology received its international passport in the early 70s, when the Department of Transportation of the United States of America sponsored a study to define an ***Advanced Air Traffic Management System***. This was conducted at the Transportation Systems Center, Cambridge, Massachusetts. The plans were "*presented in the framework of an evolutionary system concept of traffic management* (...) *designed to meet the projected demands* for *service, safety and flexibility in a cost effective manner* [Ref. 4]. An overview report on the concept, recommended under the name "Advanced Air Traffic Management System", became available in 1975 [Ref. 5]. From then on, the term "Air Traffic Management" was adopted for a number of applications appreciably more restricted.

At the Symposium on the theme "***Plans and Development for Air Traffic Systems***" [Ref. 6], organised by the Guidance and Control Panel of the Advisory Group for Aerospace Research and Development to the North Atlantic Treaty organisation (GCP-AGARD/NATO), coincidently at the Transportation Systems Center in May 1975, the only title including these words covered precisely the presentation of the "Advanced Air Traffic Management System Study" [Ref. 4].

Four years later, a symposium sponsored by the same institution was conveniently entitled "***Air Traffic Management***" [Ref. 7]. The papers presented included "Air Traffic Management - The problem of evolving new concepts", "Helicopter Air Traffic Management System with Civil/Military Inter-operability", "Methods for Air Traffic Management", "Data link - The key to improvement in civil/military Air Traffic Management?", "U.S. Army Users Outlook on Air Traffic Management", "Very Lightweight Air Traffic Management System Using an Electronic Scan Antenna", "Precision Navigation for Air Traffic Management", "JTIDS and its Potential for Air Traffic Management".

***The terminology had spread.***

Also in 1979, the Commission of the European Communities invited Industry to conduct a study outlining the possible "***Impact of technological development on Air Traffic Management***" in the first quarter of the 21st century.

The study was to cover several areas including air-ground and ground-ground communications, airborne and ground-based navigational aids and radar components. The conclusions of the study emphasised the technological development forecasts in the essential subsystems, but it also made recommendation to assess, among other essential aspects, the future air traffic demand and the basic structure of the future air traffic management system itself. Clearly, in this context, as in the initial American study (AATMS), the scope of ATM is extremely wide and can possibly be summarised as an optimum use of available resources leading to an efficient conduct of air traffic. But,

as already mentioned in the previous paragraphs, the same term - most often adequately qualified - has been used in an appreciably more restricted sense, although possibly in a more precisely defined way.

Air traffic flow management, previously mentioned in parallel with the FAA Central Flow Control System, is an example of this. An illustration of its practice in a specific European country is presented in Reference 9 for the United Kingdom. Obviously, ***air traffic flow management*** is part of the overall air traffic management, in as much as ***it aims at adjusting demand and capacity***. The look-ahead time is appreciably reduced when compared to the Department of Transportation, DOT, or the Commission of the European Communities, CEE, 10 to 25-year scales. It varies from say 6 months for demand scheduling management to a few hours for short notice constraints.

With slight extrapolation, it could reasonably be said that air traffic flow management is to deal with all factors - conceptual, structural, technological, procedural, operational - affecting the demand/capacity relationship, including, in particular, the prediction and possibly the smoothing of the demand and insuring an adequate specification and a maximum and efficient use of the handling capacity. Timescales may vary from 20 years to say 2 hours when referred to actual air traffic controller actions.

Short-to-medium-term components of air traffic management - with respect to on-line operation - have been defined. These sometimes refer to specific geographical regions such as en-route, terminal or extended terminal areas. This provided the opportunity to place the emphasis on the difference between air traffic management and air traffic control. Indeed, so far there was no confusion between both concepts since management was appreciably ahead of on-line operation. Some twenty years ago, Ratcliffe [Ref. 10] proposed a presentation of the actions affecting the safe and expeditious conduct of air traffic based on the magnitude of the look-ahead time : from 20 years for long-term planning (airport, air-route structure, etc.) down to 20 seconds for automatic collision avoidance. This classification clearly shows the position of any sub-system in a given air traffic management/air traffic control system concept. It would be most useful, if following this idea any designer of particular "sub-systems" would indicate where his product falls along that timescale.

The organisation of the traffic in terminal area received particular attention since arrival delays were expected and were later observed at high-density traffic airports. The terms used to describe the approaches proposed varied [Ref. 10], but soon expressions like "***management of air traffic in terminal areas***" appeared to cover a wide range of developments [Refs. 11, 12]. Sometimes, as in Reference 11, the authors wished to make sure that it is understood that both management and control aspects are covered in their studies. In other studies, the terms "control" possibly qualified as "***dynamic control***" and similarly ***scheduling and sequencing*** are used only, but clearly the developments include management aspects [Refs. 13, 14].

More recently, large-scale projects have included the term Air Traffic Management, fortunately with some additional qualifications, making it clear that it applies to specific situations, well defined both in time and/or in space. The project "***European Air Traffic Management System***", EATMS, as part of the European Air Traffic Control Harmonisation and Integration Programme, EATCHIP, constitutes a very clear illustration of a broad terminology covering a well specified work programme [Ref. 15].

*Accordingly, and with all the precautions resulting from the preceding paragraphs, we dare to risk a simplified picture of* ***air traffic handling*** *in the following section.*

## 5. HANDLING OF AIR TRAFFIC[2]

Air traffic, perceived as a collection of aircraft, whether carrying passengers, freight or mail, or accomplishing specific civil or military missions, exhibits a number of facets which may be divided into two main categories related

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[2] *The following paragraphs are partially abstracted from a lecture delivered several years ago at the Advanced Workshop on* "**Flow Control of Congested Networks : The Case of Data Processing and Transportation**", *organised by the Consiglio Nazionale delle Ricerche (Research Project on Transportation) in cooperation with the Scientific Affairs Division of the North Atlantic Treaty Organization (Capri, Italy, 12-17 October 1986) and published subsequently under the title* "**On-line management and control of air traffic**", *in the NATO ASI Series,* "**Flow Control of Congested Networks**", *Series F, Vol. 38, Springer-Verlag, Berlin, Heidelberg 1987.*

to its ***constitution*** and its ***handling***. The two categories are not independent ; for example the constitution of a given fleet clearly influences the means required to handle it. The elements determining the traffic constitution include the distribution, nature and densities of connections and the fleet composition, namely types and quantities of aircraft, avionics included.

***The national and international civil and military authorities will define and provide the means (facilities, techniques, procedures, man-power) to handle the actual traffic in a safe, smooth and efficient manner.***

**Management / control**

The handling of air traffic could then be considered as including two essential aspects currently called "management" and "control". In the previous sections, we have summarised the essential characteristic steps in the historical development of management terminology. In short, ***management deals with collections of aircraft, while control applies to individual flights***. Also, in terms of timescale, control constitutes the on-line component of air traffic handling while management operates "upstream", as far as 20 years ahead.

Clearly, whatever their subsequent effect on flight efficiency (safety, expedition, consumption, economy, capacity), measures undertaken several hours to several years before the flights concerned enter the area of control, have no direct bearing on the on-line definition of the related trajectories. With respect to an area of control, this is the case for all measures undertaken by a management unit organising or limiting the traffic prior to its entry into the area concerned. The last of these units, chronologically, is the flow management cell upon which the area of control depends. By contrast, measures taken as a result of modifications to the overall traffic existing in a given area generate control directives to be implemented immediately and/or shortly thereafter. This management component, which operates on-line, together with the actual control which results, will be discussed further later in this paper.

**Timescales in air traffic handling**

In order to place and illustrate the relative positions of control and management components in the overall set of ATM/ATC actions, use could be made of Ratcliffe's ATC scale [Ref. 10], duly adapted to cover recent developments and related terminologies.

**Air traffic management**

A number of management actions have been taken well before any aircraft enters the space/time area of control. These actions include the planning and implementation of new main facilities, the introduction of conceptual approaches which reflect advances in relevant technologies, the reorganisation of the airspace resulting from revisions of national and/or international policies and all measures taken well in advance in order to make demand compatible with potential or available services.

All these measures are included under Air Traffic Management (ATM) and the related look-ahead timescale extends from 20 years or so, down to a few weeks. Examples of such actions include the planning and construction of additional airports, new routes and possibilities for area navigation, replacement or upgrading of navigation aids (such as the use of satellites [Refs. 2 and 3], introduction of a microwave landing system [Ref. 16], upgrading of an instrument landing system from one category to the next wherever applicable). They also include consideration and development of advanced air traffic handling concepts and their progressive introduction into operation [Ref. 17], the specification and design of new control centres [Ref. 18] and some of those long-term actions aimed at making demand compatible with available services.

**Air traffic flow management**

In the chronological and hierarchical control loop handling air traffic, the next series of measures includes the air traffic flow management (ATFM) actions. The relevant look-ahead time extends from a few months down to a few hours. Essentially, air traffic flow management aims at reconciling demand and capacity. It ranges from demand-scheduling management (3 to 8 months) to short-notice constraints (2 to 24 hours). The departure scheduling at main airports - with a look-ahead time of the order of 6 months - falls within this first category of ATFM actions. It was introduced in Europe, initially at London airport, U.K., as a result of V. Attwooll's work [Ref. 19].

**On-line air traffic management**

This particular component of air traffic handling deals with collections of aircraft in a way appreciably different from Air Traffic Flow Management. When aircraft enter the relevant handling area, an assessment of the overall situation

is made (aircraft requests, traffic situation, capacity usage, overall and specific constraints) on the basis of which guidance directives are generated and issued either directly or subsequently to these particular aircraft; guidance corrections for some of those aircraft already in the area may result.

The relevant timescale depends on the extent of the handling area. In Western Europe, an adequate estimate would range from approximately 30 to 40 minutes for possible implementation in the not-too-distant future to approximately 1 to 2 hours for use in a truly integrated European Community. These considerations will be elaborated upon further in subsequent sections.

**Air traffic control**

The Air Traffic Control elements will implement the guidance directives generated by a regional air traffic management unit. Depending on the organisation of the airspace "jurisdiction", the related timescale may be of the same order or appreciably reduced as in the present practice.

**Collision avoidance**

There is no need to dwell on this particular safety component: it should come into action only if all the other separation measures have failed , that is to say when a pair of aircraft on a collision course have slipped through the meshes of a 2-to-5-minute safety net and, as a consequence, a possible disaster is imminent. Depending on the system and/or the geographical area, the avoidance directives could be generated either on the ground and automatically relayed to the aircraft, or directly in the cockpit. A typical timescale might vary from 60 to 20 seconds.

## 6. INTEGRATION OF CONTROL PHASES

**Earlier developments**

For over 15 years, we have been advocating accurate prediction of aircraft trajectories over extended areas in order to provide optimum or quasi-optimum flights for the airlines and other operators (Refs. 20 to 25).

In 1975, Erwin [Ref. 26] proposed a detailed concept, in which "*the Air Traffic Control system defines four-dimensional tracks for all arrivals that will derandomize and space traffic for landing on the runway*". Among other aspects, the author rightly places emphasis on the controllability of flight time in terms of total path length and speed versus altitude aero-performance limits. It is worth noting that even at that time Erwin estimated the range of time-of-transit controllability, on the basis of total flight distance to touch-down, to be of the order of 200 nm. This clearly suggests a real integration of the control phases, covering landing, approach, descent and cruise, or part thereof.

Most of the efforts initiated in the same period, or slightly later, which were aimed at reducing the stacking penalties, make the same basic assumption either explicitly or merely implicitly: integration of control phases should be over an extended area corresponding to flight lengths of the order of 150 to 300 nm from touch-down. Previously, an approach such as Erwin's was often qualified as "strategic" [Refs. 12, 27, 28]. Today, for the same look-ahead time, the term on-line regional management is preferred by the author, implying without ambiguity that both prediction and subsequent trajectory control are covered in a tight overall control loop, as outlined below *(see also note page GI-8)*.

**European scene**

In Europe, Brussels (Belgium) is less than one hour's flying time from the main airports of the adjacent countries. Several years ago, for the purpose of investigating the effect of excess route lengths on fuel consumption in Western Europe [Ref. 29], an international network was considered, made up of those routes connecting the capitals (or cities where the main airport is located) of the eleven States that participated at the time in the EUROCONTROL Route Charges System. In such a European network, the length of a flight averaged over the yearly traffic was found to be of the order of 300 nm.

This average length would be reduced further if the complete network, i.e. including domestic traffic, were considered. Accordingly, "given the geographical and timescales involved, it should be possible to organise flights in Europe, including the departure and arrival sequences, in such a way that any aircraft cleared to depart would land at its destination after a flight conducted in accordance with airline policy, without alterations resulting from

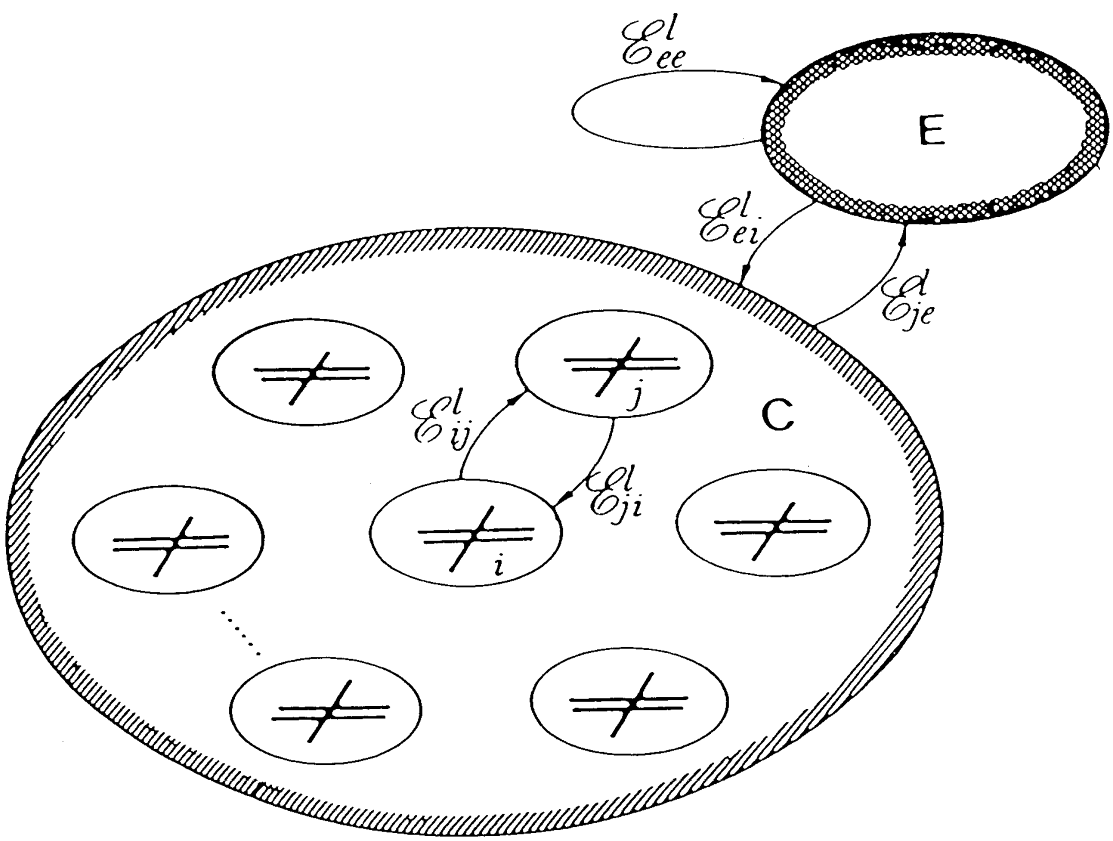
short-term planning and subsequent directives that are disruptive to the air traffic" [Ref. 30]. This prompts recommendation of an approach consisting of the central on-line handling and regional control of air traffic, as described in the following section.

**On-line handling of air traffic**

The future handling of air traffic in an extended continental area such as Western Europe (C in Figure 1) can be described schematically as follows. The airspace external to this extended area is labelled E.

The overall area (C) includes a set of regional sub-area (such as sub-areas i or j in Figure 1). Each sub-area includes a main terminal and possibly additional secondary airports. Four main categories of traffic can be identified according to origin and destination, viz. :

- origin and destination inside one and the same sub-area (regional traffic);
- origin and destination located in two different sub-areas (Western European traffic);
- origin only or destination only inside overall area C (traffic originating or terminating outside the area);
- origin and destination both located outside overall area C (overflying traffic).




**Flows of traffic in an extended management/control area**

**Figure 1**

In order to handle the traffic efficiently, a centralised on-line overall management unit will be required to be set up. For each aircraft entering the system, i.e. entering the extended area C either from inside (departure from one of the sub-areas) or from outside (either with a destination inside C or not), this unit generates the relevant 4-D trajectory and possibly amends the trajectories of some of the aircraft already in the area, to minimise the global traffic cost incurred by the operators.

The main control variables include the take-off and landing sequences over the area, with associated transit times, these two sets of variables being subject to quite different sets of constraints. The related trajectory control directives are dispatched to the regional control units for implementation.

From a **scientific viewpoint**, methods of optimisation are available to approach such a complex problem and the relevant calculations are likely to be compatible with real-time computer operation. Preliminary investigations have indeed been made in this direction. An analysis of the overall control problem was presented some years ago [Ref. 31]. This last reference also contains an extensive - although not exhaustive - bibliography on the subject as available at that time.

**Technically**, the global optimisation approach is certainly feasible, but a number of areas will need basic research and fundamental development. In particular, this applies to the ground movements, the 4-D update of meteorological information, and the generation of fully reliable directives for accurate guidance of aircraft of all categories. The advent of Mode-S in the field of surveillance will very likely be sufficient to complete the **technology** support required including data link capacity.

The essential **man/system** interface problem will probably be much easier to solve than is believed today. The new generation of air traffic controllers, either supervising a central unit or implementing the guidance directives regionally, will communicate with the overall traffic/aircraft guidance optimiser as he or she would with a friendly adviser, in simple terms and in full confidence. As a consequence, the **operational** conduct of traffic should take place smoothly.

Greater difficulties would certainly appear at the **organisational** level in a number of areas; these include the definition, collection, transfer and on-line processing of information, the standardisation of protocols for automatic exchange (ground/ground; ground/air) of information to be used on-line, structuring the jurisdiction of the corresponding reorganised airspace, etc.

At some stage of European development, it will be possible to effect such an integration of air traffic handling - with on-line management and control, departure and arrival sequences as essential parts of the control variables - and it is now opportune to initiate the basic developments required to meet such a stimulating challenge.

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*Note :*

*In this context, a friend of ours, Dr U. Völckers, Developer of the COMPAS System, DLR - BFS, Germany, drew our attention to an early paper, by E.G. Bowen and T. Pearcey, Sidney, Australia, published by the Royal Aeronautical Society, London **1948**, entitled "**Delays in the flow of air traffic**".*

*This paper clearly suggested and also recommended a scientific approach to the overall air traffic handling and expressed the initial conditions in a way which, subject to minor adjustments and appropriate upgrading, remains valid today.*

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# CHAPTER 1

## THE AIR TRANSPORT SYSTEM

# THE AIR TRANSPORT SYSTEM

by

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## 1. AIRCRAFT AND AIR TRAFFIC CONTROL

The number of passengers travelling by air is still in constant growth, at a rate of something like 5 % per year. Owing to a present overcapacity offered by airlines, mainly in Europe and the USA, the number of aircraft is expected to double in 10 or 12 years and triple between 15 to 20 years from now. No noticeable development of VSTOL and helicopters for passenger traffic is expected, mainly owing to acoustic and chemical pollution and higher operating costs. More details will be given in the next chapter. In many parts of the world, congestion exists both at airports (and in TMAs[1]) and on many routes or trunks. Navigation is governed by rules which have not changed for a long time: it should be noted that international agreements are mandatory for any modifications in the rules; the ICAO[2] establishes the rules and nations are invited to adopt them. For the moment the airspace up to a certain FL is under national sovereignty. This is why national acceptance of ICAO rules is still a necessity. However, the structure of airways, the approach from the "Top of Descent" (TOD) and the final approach specifications are under national responsibility, subject to general guidelines and guidelines on standards governing ground equipment issued by ICAO (For example: radio beacons or ILS specifications).

There is no hope of accommodating traffic twice as great as today's traffic with the existing overall Air Traffic Control structure. New concepts must be looked for; this paper tries to make some suggestions with a view to the ATC of 2000 and beyond.

Let us first comment on the high degree of sophistication of modern aircraft and the existing ATC which is a "manually operated system" - albeit greatly assisted by electronic aids.

The guidance of an aircraft, which includes the control of the attitude and the velocity of the aircraft, requires the control of 4 main parameters (pitch, roll, drift, and power) with absolute limitations on the aircraft state. This is a technology-driven problem, i.e. a problem for which mathematical solutions exist. In the case of modern aircraft a commercial flight can be described as a sequence of automatic phases, engaged manually by the pilot from brake release to landing. In the most advanced aircraft, the flight is under FMS (*Flight Management System*) control and can be considered as automatic except for acceleration on the runway, "rotation" and the setting of the attitude for the initial climb. However, flights are far from automatic at the present time, because aircraft are not alone in the sky, many interferences with other aircraft occur during the flight and trajectory parameters require to be reconfigured many times, e.g. during climb and descent. Communications between ground control stations and aircraft are still by voice (VHF or UHF or HF) as they were 40 years ago!

The management of a fleet of aircraft in a 3-D space with either constraints on the time at which an aircraft is supposed to fly over a beacon (3,5-D navigation) or velocity constraints at any time (4-D navigation) is a much more complicated problem than the control of an aircraft to satisfy navigation constraints (3, 3.5 or 4-D).

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[1] *TMA: Terminal Manoeuvring Area.*

[2] *ICAO: International Civil Aviation Organization. ICAO, 1000 Sherbrooke West, Montréal QUE HSA 364.*

At any time, aircraft must be separated by specified distances and the instructions transmitted to the pilots should be such that the pilot can comply with them safely, i.e. the aircraft must always fly "inside its flight envelope" (see 6.3). Aircraft can interfere with each other at any time; they must fly along routes, i.e. on a ground-reference positioning system for the horizontal projection of the routes and rely on the atmosphere (barometric pressure) for "altitude", while the parameters used to control the aircraft are an inertial reference and atmosphere-reference system. The wind interactions or, at worst, the wind gradients in which two (or more) aircraft fly must be anticipated and taken into account by ground control to achieve correct spacing and scheduling of aircraft. This is no longer a technology-driven problem; it is a *multi-agent problem with interaction in a random environment.*

Full automation of Air Traffic Control is not achievable before year the 2015...or 2025: it is not an objective of today's studies. As we shall see later on, many electronic aids are in use or being tested. They will be improved and extended soon, but clearly for the next 10 or 15 years, at least, the final responsibility will still lie with the controller. On the other hand we can say that, if we decide now to manufacture an aircraft which can perform a flight in fully automatic mode from brake release to landing and braking, the aircraft would be developed within 5 years and certified - the phases to be automated are acceleration on the runway, "rotation" and the setting of the initial climb[3]. In order to comply with current safety levels - some $0{,}5\ 10^{-7}$ /h of flight - additional failure detection and automatic reconfiguration must be provided, tested and certified. As to taxiing on the apron, projects for automatic tractors are already under study...

The former concept of ATC is now only a part of what is called ATM (Air Traffic Management), which is made up of three components:

ASM: Airspace Management. It includes the concept of direct routing from origin to destination (open skies concept), in fact from the "exit point" to the "entry point" of the airports concerned. At the present time the semi-open skies concept is sometimes used; it is a combination of route structures in the TMAs and direct or close to direct routes from the "exit point" to the "entry point" of the TMAs.

ATFM: (Air Traffic Flow Management). Normally every evening ATFMs decide the maximum flow which can be reasonably envisaged for the next day. The opening of the EUROCONTROL-operated CFMU (Central Flow Management Unit) in 1993 will probably improve national ATFM decision-making. If domestic traffic is not dominant, the need for coordination with adjacent and even distant ATFMs is a necessity. The CFMU is expected to improve greatly the forecast of acceptable traffic inside Europe.

ATC: This is the "conventional" real-time centre which controls each IFR flight (and may advise VFR flights) in order to ensure separation between aircraft and guidance to their final destination.

Let us analyze how a commercial flight is performed today.

## 2. A TYPICAL COMMERCIAL FLIGHT

We are considering the Air Traffic System defined as follows: aircraft at the parking bay after passenger loading, ground movements, take-off, climb and navigation, cruise, descent, approach, final approach, landing, ground movements, and last stop at the destination parking bay.

Figure 1 represents the vertical profile of a typical flight, a profile which has been stable for decades. Figure 2 represents the flight envelope for an aircraft (say an A320; note that the diagram refers to a mass, a balance and a plane configuration).

Such a profile raises 3 comments :

a) It is close to an optimum profile with regard to a criterion for minimum fuel consumption when the aircraft is used in the vicinity of operational maxima ($V_{MO}$, $M_{MO}/Z$); it is not optimum with regard to a minimum flight-time criterion.

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[3] *Acceleration on the runway, rotation and the initial climb do not correspond to any mode of the automatic pilot (AP), and the difficulties in automating these phases come from the difficulty in entering lateral gusts, overcoming the failure of one engine and the impossibility of using ground referenced trajectories as in the case of an ILS landing. In addition, there is a continuous transition from a ground vehicle (such as an automobile) and a plane during the acceleration phase.*

If there were no air traffic constraints, then the profile could be modified as follow :

<u>Phases C,D,E</u> : to use the optimum climb from the safety height (1500 feet) up to the altitude of the beginning of the cruise. The gain will be small. Note that the climbing rules used today are easy to fly because they concern <u>indicated airspeed</u> (IAS) and not true airspeed (TAS) - Fortunately such rules are not far from the energetic optimum resulting from the $C_L/C_D$ variation with regard to airspeed and from the thrust/speed relation.

<u>Phase F</u> : except for Concorde, aircraft are assigned to fly at constant levels; for long flights the aircraft becoming lighter, the optimum cruise would be an ascending one, an unacceptable procedure in the crowded airspace such as the North Atlantic Area at FL 330/390[4]. However each time ATC may possibly assign increasing FL by 2000 ft steps during the cruise phase.

<u>Phase G,H</u> : the beginning of descent is such that a Flight Level Stabilisation should be reached just before the reporting point.

<u>Phase I</u> : if too great a number of aircraft are arriving in the same time slot, holding should be provided; can be on a predetermined pattern or a modification of trajectory under permanent radar control. This is the only way to secure the traffic flow.

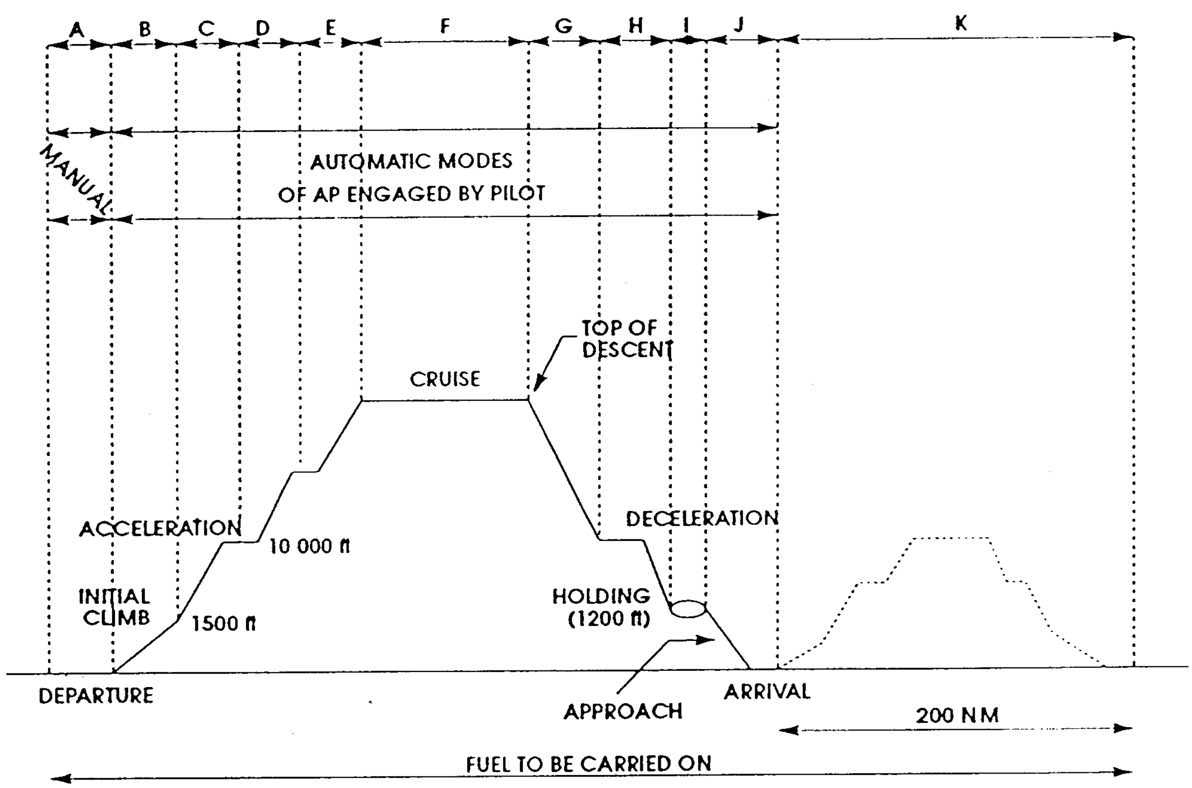


**Figure 1**

**Vertical profile of a flight**

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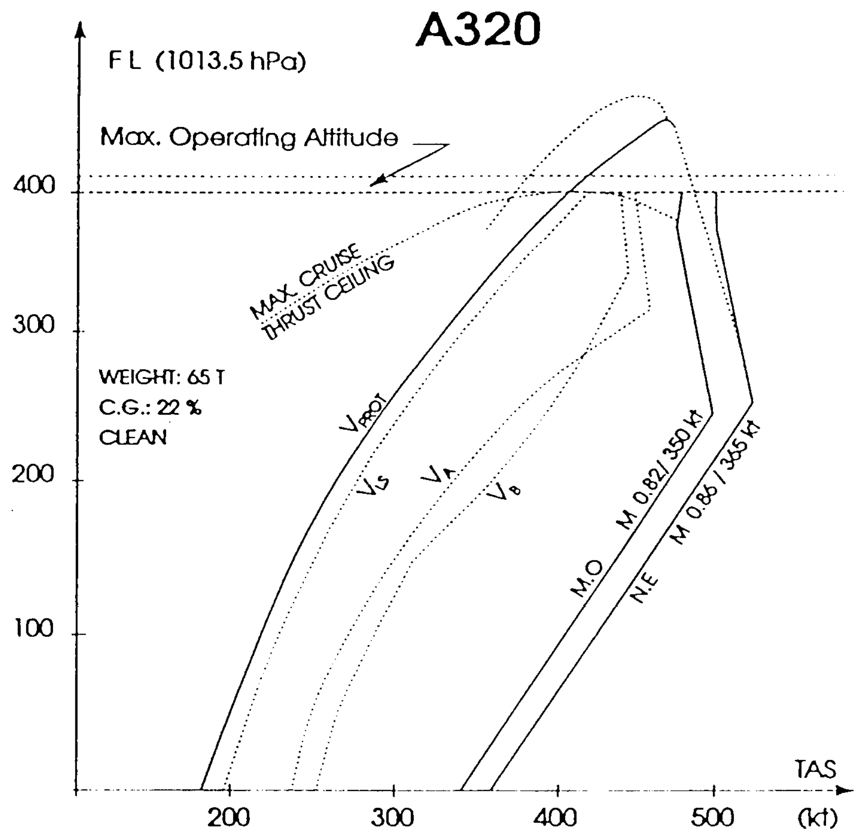
[4] *Concorde initiates its supersonic cruise at 11.2 km and finishes it at 15.8 km of altitude.*




<u>SPEEDS DEFINITION</u>

$L_S$ : Lowest selectable speed. It corresponds to 1.13 $V_S$ during take-off or following touch and go. It becomes 1.23 $V_S$ as soon as any flaps/slat selection is made.

$V_A$ : Design speed for maneuver

$V_B$ : Design speed for maximum gust intensity and rough air speed (JAR 24.335 (d))

<u>HIGH SPEED PROTECTION</u> :

MMO/VMO : M.82/350 kt
$M_{MO}$+ 0.04/$V_{MO}$+15 kt : maximum steady speed with full nose down stick.

<u>HIGH ANGLE ATTACK PROTECTION</u> :

This protection has priority over all other protections.

V prot : min speed (corresponding angle of attack : alpha prot).
If alpha prot is exceeded, the angle of attack returns to and maintains alpha prot.

**Figure 2**

**Flight envelope (A320)**

Phase J : final approach: all major airports are equipped with ILS, which allows approaches as described in Figure 3. Normally, a beacon (ADF, VOR, LOC) is located between 5 and 10 nm beyond the threshold of the runway, and enables easy capture of the ILS localiser (and generally enables close holding if necessary). During the final descent, other beacons (Outer Marker: OM; Medium Marker: MM; and Inner Marker: IM) enable aircraft height to be checked at specific points.

The alignment on the beam, at least 5 nm ahead of the runway is a constraint which MLS would have palliated. However, it is quite certain that the MLS will not be installed at a world scale; GPS, mainly differential GPS (diff-GPS) are simpler and cheaper systems for the on-board equipment and combination of diff-GPS and ILS may allow final approaches "in curve".

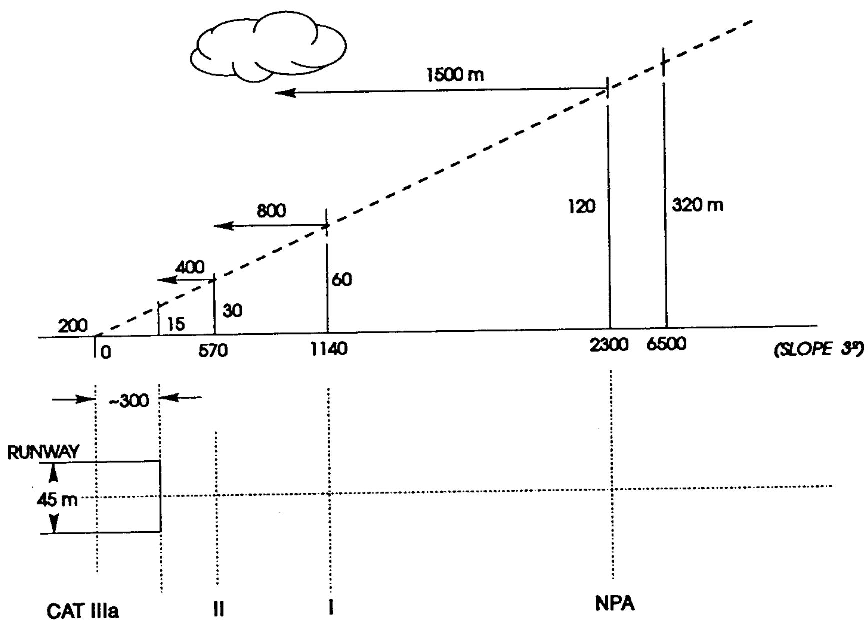



**Figure 3**

**Landing "categories" (CAT I, II, and III)**
**(NPA = non precision approach)**

Phase K : ground movements from the runway to the parking bay. It is also a traffic management problem which is poorly handled, and would therefore slow down the traffic if action were not taken promptly. Some suggestions will be addressed later on (Chapter 10).

b) All phases except phase A (acceleration on the runway) and the beginning of B (initial climb) may be performed in an automatic mode, according to the pilot's choice, (including the landing and the braking on the runway): the pilot then engages modes of the Automatic Pilot. On certain aircraft engagement can be automatic, thanks to FMS.

c) Current statistics show that accidents do not occur with the same frequency in all the phases of the flight (Figure 4). the most critical phases are take-off and the initial climb - the main reason being failure of one engine - and the final approach and landing. We must focus our attention on these phases.

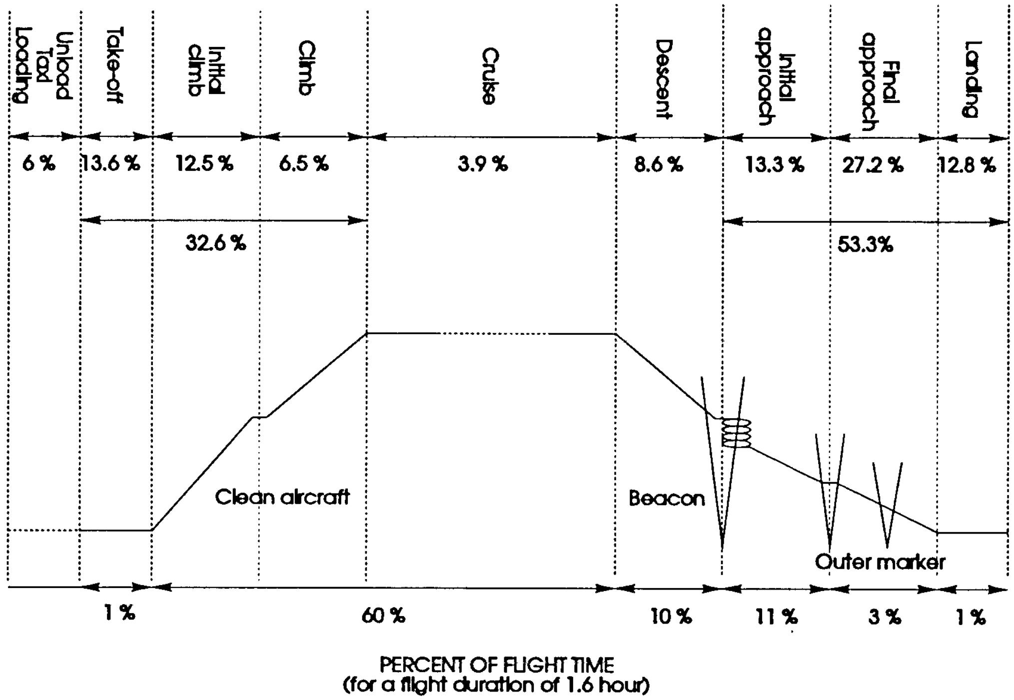



**Figure 4**

**Probability of fatal accidents**

A word about statistics, or at least on the significance of the statement that "80 % of aircraft accidents are due to human error" (NASA, FAA, DGAC). This statistic comes from the analysis of accidents which have been carefully studied by a commission. But probabilities, by definition, are the ratio between the number of events causing accidents and the total number of events which could have caused accidents. Therefore it should be necessary to take into account all cases when an accident could have occurred had man not intervened. But such cases are never taken into account in the statistics, even if the crew has duly reported the incident. Consequently, the assertion that "80% of accidents..." results from a biased computation, and should be taken as a minor indication.

d) Given the safety level achieved by jet engines, twin-engine aircraft are now allowed to fly over oceans or large uninhabited countries if the operator can prove that the aircraft can safely reach an airport, with only one engine, located 180 mn from the engine failure point (ETOPS concept = extended twin operations). Some 5 or 6 years ago this was only 120 mn and when first authorized some 10 years ago it was 90 mn. More generally, if we consider the probability of fatal accidents occurring in the various phases of a flight (Figure 4), the probability that the cause of the accident is engine failure is only 12 % - Note that the in-flight shut down (IFSD) rate is of the order of 2 for $10^5$ hours of flight (for modern high by-pass ratio engines).

## 3. THE PROBLEM

In view of a slowly continuous traffic growth and with the constraint of maintaining (or improving) the present safety level we think that it is time to consider the Air Transportation System "from home to home" as a unique problem and no longer, as a collection of independent problems to be solved. This is the "System Approach" concept.

In this paper we will consider mainly the sub-system "from block to block" and more precisely the optimization of Air Traffic Control. However in the last chapter we will consider the Airport sub-system (including the associated TMA); this sub-system is highly interrelated to ATC; it is also tied to the passenger behaviour because, finally, what has to be optimized is the passenger's satisfaction.

# CHAPTER 2

## AIR TRAFFIC COMPLEXITY

# THE AIR TRAFFIC COMPLEXITY

by

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## 1. RANDOM ENVIRONMENT OF AN AIRCRAFT

This is a typical characteristic of aeronautics. Marine and space exercises have to cope with adverse conditions, but probably not on the same level as in aeronautics.

To design an aircraft, it is first necessary to specify a "standard atmosphere" (Figure 1) in order to compute the aerodynamic forces and associated phenomena, such as "buffeting" and "flutter"[1]

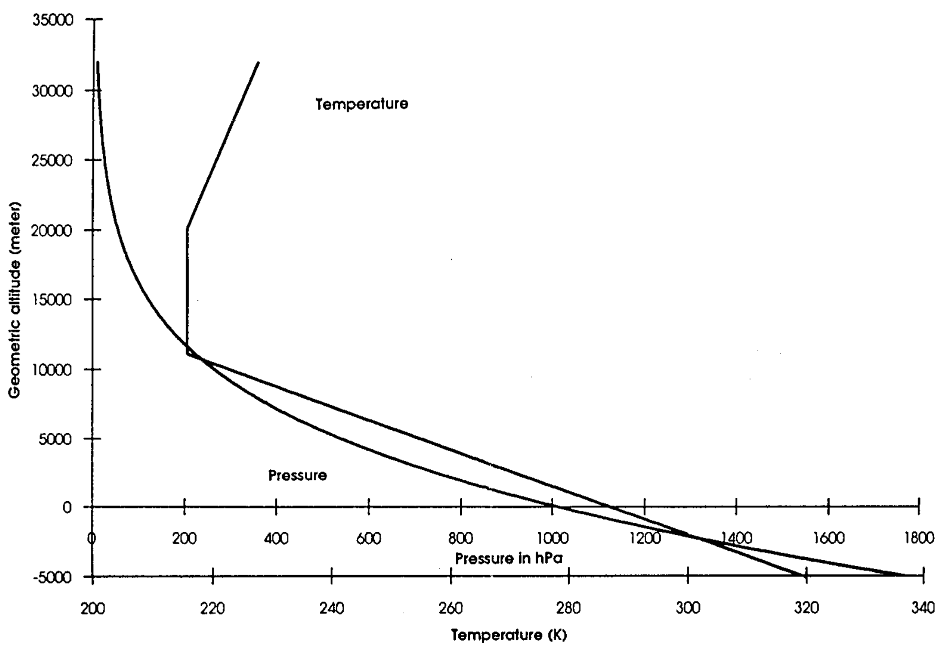


**Figure 1**

**Standard atmosphere**

[1] *This is an aero-elastic coupling between the external flow around the wing and the elastic modes (bending and torsion) of the structure of the wing. It is a dangerous phenomena - Civilian plane are always flutter-free.*

The performances of the aircraft are summarised in the flight envelopes (see Figure 2 in chapter 1). There is one flight envelope for each type of aircraft (if an aircraft can be fitted with different types of engines, there are as many types of aircraft as types of engines), for each weight (within a range), for each balance figure (position of centre of gravity), and for each load factor.

Airlines and air traffic controllers use these envelopes to optimise flight conditions.

However, the actual atmosphere in which the plane flies differs from the "standard atmosphere". The *local atmosphere* constantly varies during the flight. The prediction of the main characteristics of the atmosphere ahead of the plane will soon be possible (3 to 5 years). We will return to this problem in chapter 10.

The lower levels of the atmosphere are composed of :

- the troposphere, a layer around the earth which extends to an altitude varying between 8 km and 11 km, according to the latitude and the season of the year;

- the stratosphere, the layer above.

In the "standard atmosphere", barometric pressure and static temperature are specified. In the troposphere, temperature decreases uniformly from +15° to -56°C at 11 km. It then remains constant for 9 km and thereafter increases slowly to +15°C at 70-80 km.

The structures of these two layers are quite different. In the troposphere, convection currents prevail. This is a vertical transfer of molecules. In the stratosphere, the molecules circulate parallel to the earth's surface for a long time.

Most commercial aircraft fly at constant altitudes between 0 and 11-12 km. Military aircraft, (or spy aircraft such as the Lockheed ER-2), fly much higher (up to 27 km).

Concorde has an ascending cruise starting at 11 km and terminating at about 15,8 km (depending on the length of the cruise phase). There are two reasons for this :

a) this is an optimum trajectory with regard to fuel consumption (the aircraft is flying at the optimum lift/drag ratio during the whole cruise flight. With the mass of the plane decreasing and the thrust being held constant, the plane achieves a positive vertical speed) ;

b) there is no other commercial traffic in this altitude range.

In the foreseeable future, around 2005, it is highly probable that a second generation of supersonic aircraft will be in operation. They may fly at higher altitudes and the need to have a precise knowledge of the air motions inside the stratosphere goes without saying. In a more distant future, it is possible that hypersonic commercial flights may emerge ($5<M<6{,}5$). They will reach altitudes up to 70 or 80 km.

Knowledge of the atmosphere in which aircraft fly is in fact quite incomplete. The density of measurements is frightfully low, and a coherent set of boundary initial data to integrate the equations which define air motion is therefore still a dream. Satellites provide a huge quantity of data, but the most important data, i.e. is the vertical pressure and temperature profiles all around the earth are not provided by satellite measurements.

Another difficulty lies in the fact that, at the present time meteorologists use models which do not take into account the energy exchange on the surface of the ocean (or the land), as oceanography specialists do. There is an urgent need to build a model which takes account of these energy exchanges and does not treat the atmosphere and the ocean separately (it is less crucial for energy exchange above land because of the lower specific heat of the ground; in addition, over the oceans, chemical reactions, namely with $CO_2$, cannot be ignored ; on land, the photosynthetic thermal net balance is approximately zero and only the local albedo of the ground has to be entered in the model).

Very dangerous phenomena may occur suddenly. A storm can be predicted a few hours before it breaks if *local measurements* are possible. If there are none, only the probability of occurrence can be indicated, and the detection of storm clouds - mainly cumulonimbus - is dependent on the on-board meteorological radar alone.

But there are other phenomena which are difficult to predict.

Noteworthy are *windshear*, and particularly *downbursts*. According to Prof. Th. Fujita "a downburst is a strong downdraught which induces an outburst of damaging winds on or near the ground". Damaging winds, either straight or curved, are highly divergent. The extent of downbursts varies from less than one kilometre to tens of kilometres. Downbursts are subdivided into macrobursts and microbursts accor-

ding to the horizontal extent of the damage caused"[2] [Refs. 1 and 2].

Macroburst: A large downburst with its outburst winds extending in excess of 4 km in the horizontal plane. An intense macroburst often causes widespread, tornado-like damage. Damaging winds, lasting 5 to 30 minutes, can have a speed of up to 60 m/sec.

Microburst: A small downburst with its damaging outburst, winds extending only 4 km or less. In spite of its small horizontal extent, an intense microburst could induce damaging winds as fast as 75 m/sec.

Appearance of macrobursts: because of its wide horizontal extent, a macroburst is characterized by a dome of cold air created by a succession of downdraughts soft-landing beneath the parent rainclouds. Since a dome of cold air is heavier than the warm air surrounding it, the atmospheric pressure inside the dome is higher than that around it. The pressure gradient (force, pointing outwards from the dome area) pushes the cold air outward inducing gusty winds behind the leading edge of the cold air outflow. The gust front denotes the leading edge of gusty winds which push the dome boundary away from the subcloud region.

Microbursts are different from tornadoes. Microbursts generate a horizontal vortex in the form of a ring, while tornadoes are composed of a vertical vortex only (Figure 2).

There is high risk when an aircraft is in the final approach or take-off phase especially during the 30 to 60 seconds after the touchdown of the microburst. The maximum intensity of the winds is in the 0-30 m altitude range. In this slice, winds vary rapidly both in space and time, creating severe windshear.

To give an idea of the power of such phenomena, Figure 3 indicates the shape of the wind lines, the prescribed trajectory of the aircraft (Royal Jordanian, Doha, 14 May 1976), and the real trajectory of the aircraft with the indication of the wind (direction, intensity) encountered on its trajectory. The aircraft flew in a strong tail wind, which was the real cause of the crash.

Microbursts are not necessarily accompanied by heavy rain (Figure 4) and can be stationary or moving.

Vertical downward velocities of up to 15 m/s have been measured in the centre of a microburst.

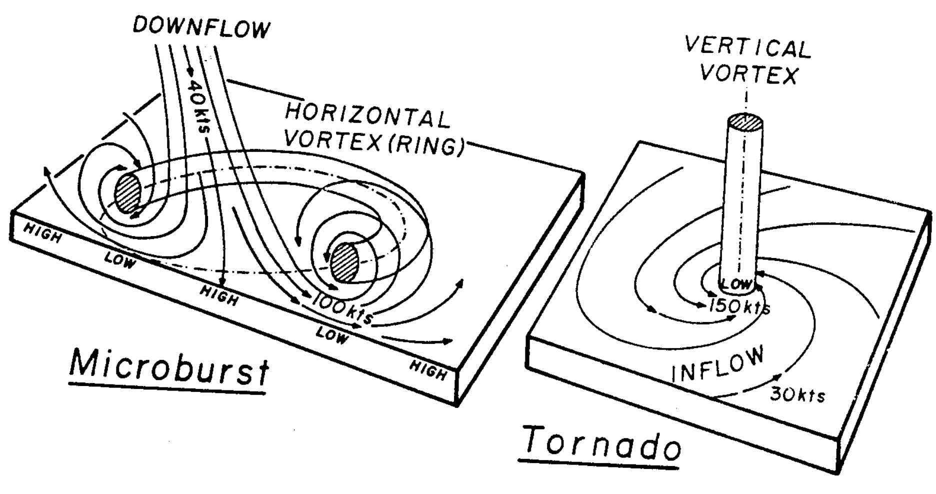


**Figure 2**

**Microburst and tornadoes (From Fujita)**

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2 *Dr. Th. Fujita from the University of Chicago has provided the clearest explanation of these phenomena in two books. See Ref. list.*

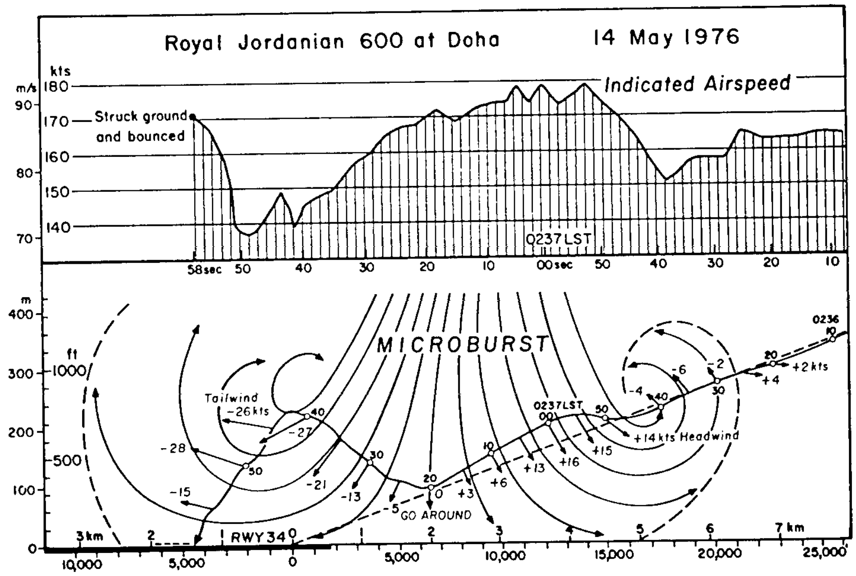


**Figure 3**

**RJ 600 accident (From Fujita)**

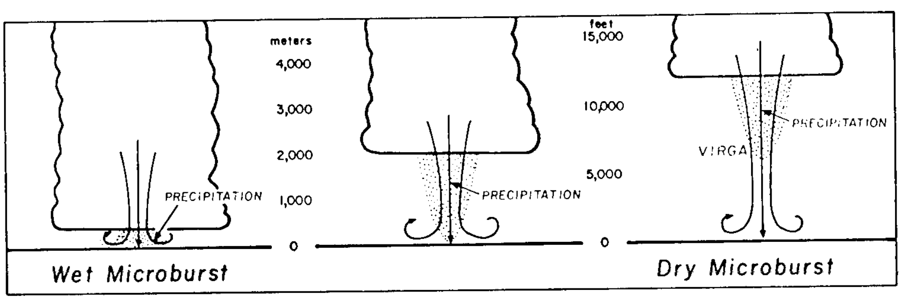


**Figure 4**

**Types of microbursts (From Fujita)**

It is estimated that at least one large commercial aircraft is lost every year (excluding USSR and China) as a result of windshear due to microbursts. There is an urgent need to detect the phenomenon at the outset, both from the ground and on board.

If an aircraft is trapped in a microburst, the action to be taken by the pilot must be rapid and precise, quite different from the instinctive primary reaction. To escape from a downburst, it is necessary to increase the total energy of the aircraft and then immediately to apply full power (it is well known that from idling to full thrust can take as long as 5 to 8 seconds). During the final approach, once the aircraft is stabilised on the ILS axis, its attitude is about 0°. The vertical speed is about 4 to 5 m/s. If a downdraught of more than 10 m/s occurs, there is no hope of obtaining a positive net vertical speed in 5 to 8 seconds. At an approach speed of about 75 m/s, the altitude will continue to decrease rapidly for 400 to 600 m before becoming positive.

However, modern aircraft already or will soon have a dedicated "mode" in the Automatic Pilot to escape from the Dallas Fort Worth (DFW) downburst as identified by Prof. Th. Fujita and now taken as a worldwide reference..

Lightning is a spectacular phenomenon but not a very dangerous one. Long-range aircraft are struck every

3000 -5000 hours while short-range aircraft are struck every 2000-3000 hours. Damage, if any, is rarely serious and destruction of an aircraft by lightning is very rare (less than 3 cases in the last 30 years)[3].

The consequences of a direct lightning strike include:

- destruction of some electronic equipment ;
- deviation of actuators for a short period if the actuators are connected to analog controllers ;
- an unexpected manoeuvre if the aircraft is digitally controlled during the time necessary to diagnose the error.

Lightning is composed of a short-duration (about 200 ps to 2 µs) impulse of several thousand amperes, with gradients which can reach 100 kA/µs. This pulse is followed by another pulse, much longer in duration (several milliseconds), with an intensity of about 100 amperes (Figure 5). Greater damage is due to the latter pulse, whereas interference from electronic equipment is due to the first pulse.

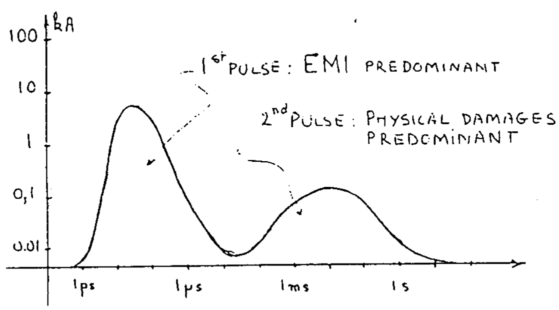


**Figure 5**

**Lightning pulses**

Icing: Recent developments in aircraft technology can be roughly summarized as follows :

a) replacement of metallic parts by composite materials ;
b) extensive use of computers and electronic equipment ;
c) high-dilution jet engine (up to 9) ;
d) autonomous navigation devices (INS) or semi-autonomous devices (GPS, Glonass).

These new technologies are not influenced by the icing phenomena except, perhaps, as a result of a) ; the difference between how ice develops on composite materials and how it develops on metallic ones is not largely significant.

The real progress comes from knowledge about icing clouds, primarily their detection from the ground and the information which can be derived for the benefit of the crew.

To conclude this paragraph, we can say that, at the present time, it is hard to predict the atmospheric parameters which an aircraft will encounter during its flight. Man's ability to collect, correlate and process the various information he receives from controllers, from on-board instruments and very often from visual observation will not be transferred to "expert processors" in the near future. On the contrary, humans sometimes take wrong decisions (namely if they are stressed or tired). Over the next 10 or 20 years, progress will develop along the lines of cooperation between "operators (crew, controllers, MET staff, etc.) and processors (incorrectly called "expert systems"). We believe that one major trend is electronic aids to be developed for the controller will be the detection of incorrect decisions: any decision could be simulated on a fast-time basis prior to its transmission man could not compete with and, thus, the consequences of such a decision could be evaluated and checked.

## 2. SAFETY IN AERONAUTICS

### 2.1 Components to be taken into account when safety is concerned

First it is reminded that the probability of natural death for a human "in normal physical conditions" is $10^{-6}$ per hour. In fact, this average varies with regard to the age (Figure 6) and it should be noticed that pilots experience one (or two, according to countries) physical examination per year and their licences are not validated if any potential disability (?) is observed by the Doctors (or Physicians ?).

This is the major reason for which there are 2 pilots on board : a civilian transport aircraft is certified for a probability of fatal accident smaller than $10^{-8}$ per hour of flight if it is piloted according to the manufacturer/airline operator instruction and if it is guided by

[3] *Lightning is very often accompanied by serious adverse atmospheric conditions such as severe turbulence and icing. More accidents are due to these last two phenomena than to lightning.*

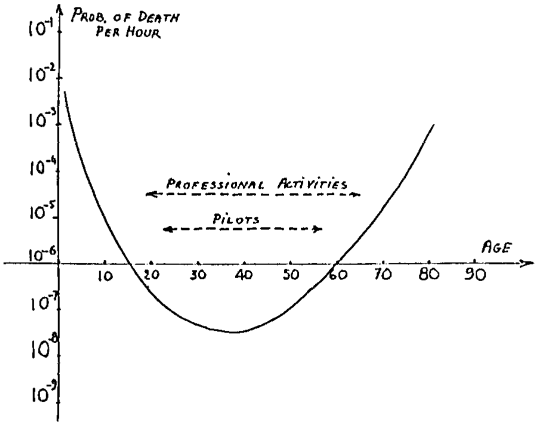


**Figure 6**

**Probability of death**

the ATC according to the rules we have seen that the probability of fatal accident depends on the phase of the flight; this figure is the average for a flight of about 1.6 hours).

It is worthwhile noting that travelling by plane is safer than by train according to the distance overide (but it is the opposite if the parameter considered is the time spent in the vehicle).

In 1991 the air safety has been slightly degraded with regard to 1990; in 1991 the number of passengers fatalities per $10^8$ passenger-km was 0,04 (35 fatal accidents involving 653 passenger fatalities in scheduled airline services) instead of 25 accidents/495 passenger fatalities in 1990 (0,03 fatality per $10^8$ passenger-km).

Now, if we look for the probabilities of fatal accidents during each phase of the flight we arrived at the ones given in Figure 4 : it is essential to increase safety in the landing phases and also take-off (acceleration, rotation and initial climb) phases.

## 3. BAROMETRIC AND GROUND REFERRED TRAJECTORIES

Navigation in TMA and "en-route" horizontal projections of the routes are specified on maps on which the latitude, longitude and height of the terrain are specified. Normally all these data correspond to an ellipsoid, the WGS-84 (World Grid System 1984). The vertical profiles of trajectories which are defined with reference to *barometric pressure*; the guidance of an aircraft is provided by ATC[4]. The vertical coordinates of an aircraft can be defined in three scales:

- according to the barometric pressure read on board as compared with the local barometric pressure at the "zero level" i.e. theoretically, the surface of the ellipsoid (WGS84) but usually the "mean sea level" (MSL)[5]. This is the altitude of the aircraft; the reference barometric pressure is called QNH.

- according to the barometric pressure read on board as compared with the local barometric pressure at the level of the ground below the aircraft (this reference is called QFE): this is the *height of the aircraft*.

- according to an arbitrarily fixed barometric setting on the on-board altimeter at 1013,25 hPa: this is the *Flight Level* (FL).

- according to the real vertical distance between the aircraft and the ground during take-off and landing phases; trajectories are "referenced" to the ground; the normal slope during the final approach is 2.5 to 3 degrees.

## 4. NAVIGATION

Let us come back to en-route navigation: normally civilian commercial aircraft fly on airways referenced to the ground in *horizontal* projection. This is both a simplification (aircraft must be only on these airways) and a handicap (the space is poorly used).

It is worth distinguishing navigation over highly industrialized countries and oceans and navigation over sparsely populated and/or less industrialized countries.

[4] *It is noteworthy that an IFR flight (below flight level 120) is safer in IMC conditions than in VMC ; indeed in that case some VFR flights could legitimately interfere with IFR flights. Anti-collision must be ensured usually by the crew.*

[5] *There is a difference of some meters between Atlantic and Mediterranean MSL ( the Atlantic is higher). The maximum difference between WGS-84 and the MSL occurs in the East of India: the difference is of the order of 60 m.*

In the former, radio beacons provide precise location of the aircraft (better than 1 nm in X and Y). In the latter, the aircraft uses location systems which can cover very wide distances such as OMEGA, LORAN-C. The accuracy depends on the position of the aircraft with respect to the transmitters.

Systems with "constellations" of satellites such as NAVSTAR or GLONASS are developing very rapidly. The location accuracy for civilian users is about approx. 100 m in X and Y, and approx. 150 m in Z. The NAVSTAR system is now fully operational (21 satellites, plus 3 spare). However, system integrity, i.e. certainty that the signals received are correct, has not yet been achieved.

Integrity means the ability of knowing immediately (to be more price, within 1 to 10s) that a failure had come in a satellite; at the present time, if such a failure occurs, for example, transmission of wrong position data from the satellite, the knowledge of the failure may be discovered only several hours after its burst by the control stations; during these hours, the users may accept incorrect data as correct ones! However, if more than 5 satellites are correctly received, automatic self contained disgnostic is provided on modem receivers.

Navigation systems using satellites will become prevalent all over the world once integrity has been achieved.

Finally, most modern aircraft, both medium and long-range, have *inertial navigation systems* (INS) which present the advantage of being autonomous but they have a drift proportional to the square of the flight time. Inertial systems using stabilized platforms are no longer being built but they are being "maintained". Modern inertial systems use gyro-laser and accelerometers as strip-down components. Gyro-laser systems, which have practically no moving mechanical parts are just as accurate; their drift is smaller and their cost smaller too.

Thanks to these means of absolute location of the aircraft within a known domain of uncertainty, we can hope that:

- R-NAV (area navigation), i.e. navigation on routes parallel to the airway 5 and 10 nm apart will be extended[6]. This will lead to better use of airspace in spite of the difficulties inherent in the initialisation and the fusion of these routes from or towards the mandatory way-points. Relinquishment of the *entry points* in TMA within the next 20 years is difficult to imagine.

- The reduction of horizontal separation of aircraft (due to the improvement of location accuracy) and vertical separation (improvement of barometric measures).

Vertical separation of 1000 feet, announced for the last 10 years, above flight level 210 seem ready to be accepted. Yet separations of 500 ft in TMA below 20000 feet are now being envisaged (it is 1000 ft at the moment).

The use of an *accuracy index* of location (3D), depending on the type of equipment used on board, to which we can associate the ground speed computed on board (4D) allows a reduction in separation between aircraft, in particular those which have similar performances and similar types of navigation equipment on board.

Guidance in TMA must be accurate and updated frequently. The approach patterns (Figure 7 and 8) are mandatory. Here again they are both a simplification and a handicap for control. "Vectoring" (radar control) is a *priori* more satisfactory for good control of the traffic flow but more difficult to manage (it requires more people on the ground). The ground speed, instead of the IAS, is the parameter which is taken into account when the aircraft is close to the final approach.

After theoretical studies and simulations performed at CERT, and subsequently by NASA/Langley[7] and Eurocontrol/Brussels[8], experiments with commercial traffic have been conducted at Brussels Airport, and they confirm the increase in landing rates that the initial studies had forecast. The gains come from better management of the traffic through the inclusion of an additional parameter: landing rates corresponding to 50 s separation in good visibility and slight cross wind (vortices escape) can be sustained.

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[6] *In the North East part of the USA where R-NAV is extensively used.*

[7] *NASA Technical Paper 2616 "Ground-Based Time-Guidance Algorithm for Control of Aircraft in a Time Metered Air Traffic Control Environment", Charles E. Knox (NASA/Langley) and Nicole Imbert (CERT).*

[8] *Air Traffic Management and Aircraft. Guidance in and around a Main Terminal. A. Benoit and S. Swierstra, Eurocontrol, to be published in "Concise Encyclopedia of Aeronautics and Space Systems" Pergamon Press, Oxford.*

Such a procedure is usually well accepted by air crew.

## 5. FINAL APPROACH

The percentage of accidents (Figure 4) shows that it is essential to increase safety in this phase of navigation.

Let us now consider the final approach phase, a phase in which the vertical position of the aircraft is referenced to the ground (no longer to barometric pressure).

The electronic aid most widely used for landing all over the world is ILS, which is composed of two features, the *localizer* and *glide slope planes*. The intersection of the two planes gives the correct path for a landing (the slope angle is normally set between 2.5 and 3 degrees).

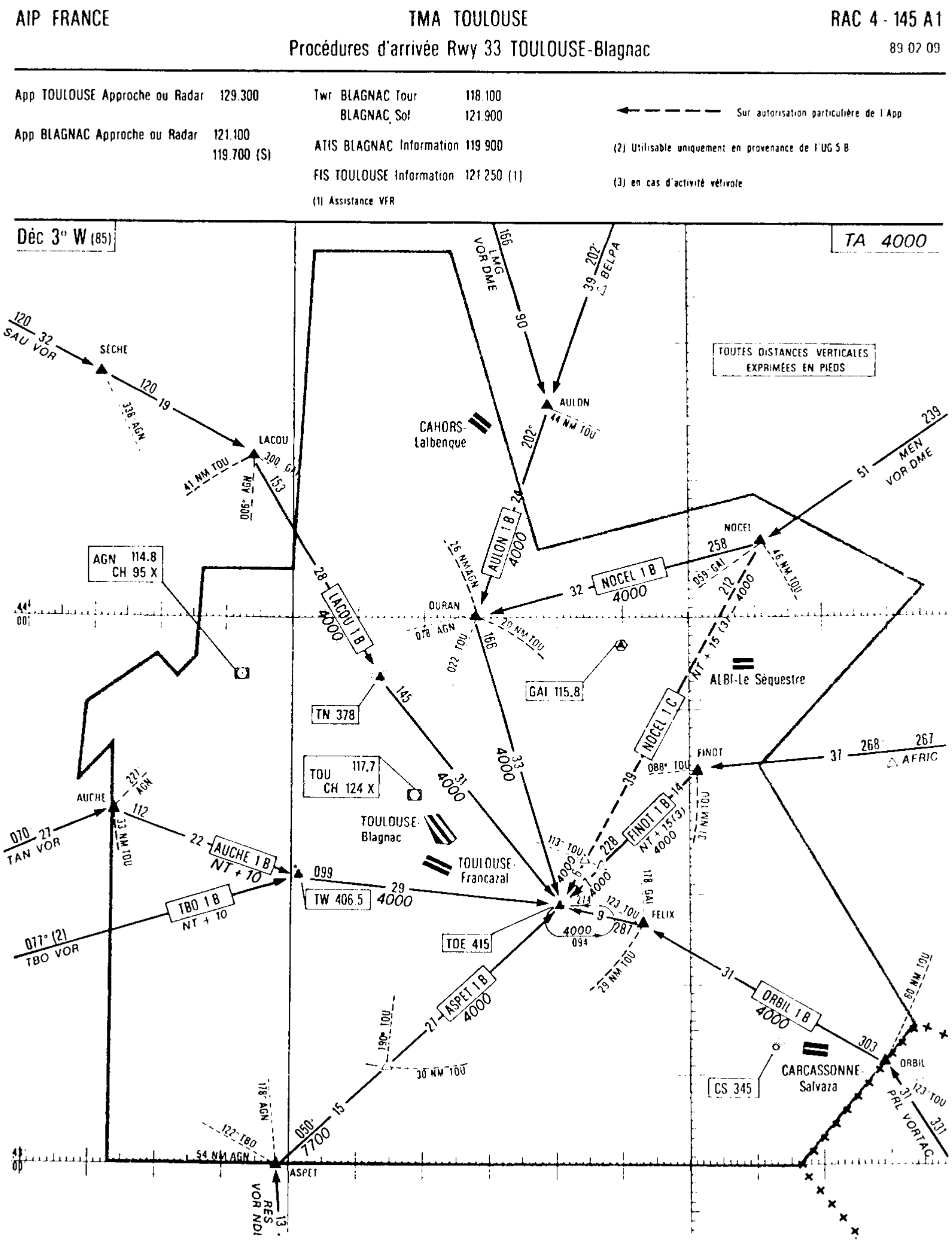


**Figure 7**

**Toulouse - Blagnac Approaches**

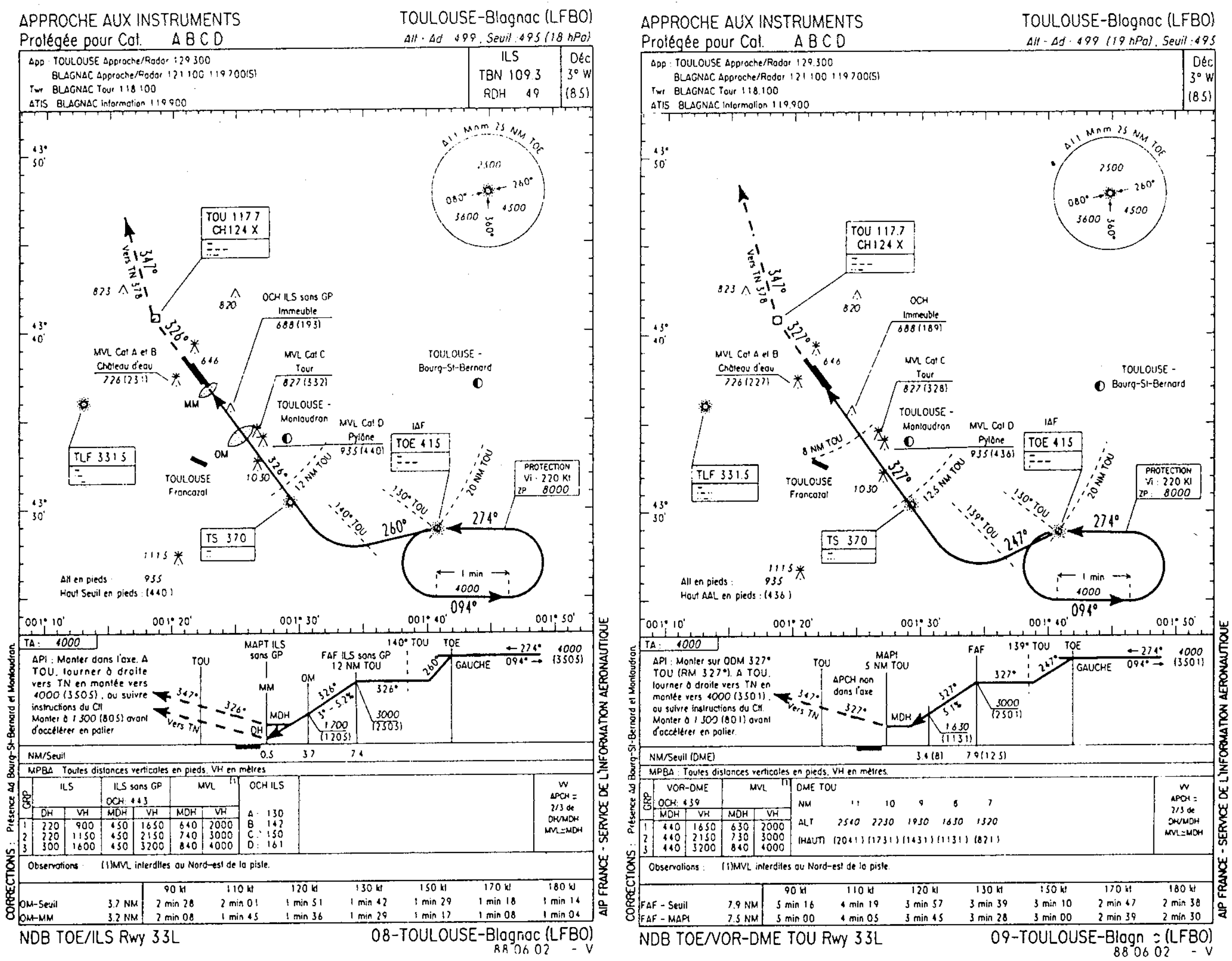


**Figure 8**

**Final Approaches on 33 L, according to the aircraft equipments**

ILS aids are divided into 3 categories : CAT I, CAT II and CAT III. The ground equipment varies according to category; CAT III is divided into three subcategories A, B and C. CAT III enables automatic landing even with no visibility. However, while vertical visibility is assumed to be 0, horizontal visibi-

lity is 200 m thanks to the high-intensity lights placed along the centre line of the runway[9] (See Figure 3).

One problem is still outstanding: the movement of the aircraft between the runway and the gate when visibility is reduced to a few metres. An oldfashioned solution is to send a car to the runway exit with a "Follow me" sign. The driver of the car may see the taxiway lights although the pilot cannot (visibility within a thin layer close to the ground is normally better than the visibility from the cockpit, i.e. from a height of 3 to 5 m).

In CAT C automatic guidance of aircraft must be provided from the runway exit to the gate. Experiments on some systems have been conducted without success. They need additional equipment on board (for example, guidance using a cable placed along the taxiways, or embedded in the concrete of the taxiway. The cable is fed with electronic frequencies and data). Great hope has been placed in differential GPS to control aircraft movement on the taxiways.

At present, most major airports in Europe are equipped with ILS CAT III, which allows landing with zero-zero visibility. In CAT III the beams are permanently checked and, in the event of power supply failure, automatically switched to another source of power in less than one second. Aircraft "certified CAT III" must carry equipment with failure detection and automatic reconfiguration after an initial failure.

In the United States CAT II and CAT III are not as popular as in Europe : of 312 runways used for commercial traffic, only 35 are equipped with ILS CAT III and 29 CAT II.

Other aids have been developed for landing and are used all over the world. The military still use GCA (Ground Control Approach), a very precise aid which unfortunately needs one qualified operator on the ground *per aircraft* during the final approach - a system which obviously cannot be extended to civilian traffic. TACAN, a variety of VOR DME, is sometimes used for CAT II landings (military aircraft only).

Many airports are equipped with optical aids (VASI, AVASI): they positively require good visibility, at least below heights of 50-30 m; most of them are composed of 2 beams, one white and one red: if the aircraft is above the optimal descent plane (2.5 to 3-degree slope) the pilot sees only white lights; if he is below the plane, he sees only red lights; correct descent plane corresponds to white and red light perception by the pilot.

Many studies and experiments are going on with a view to the use of differential GPS for blind landings, at least up to CAT II (note that in CAT II the landing is necessarily manual). GPS certification is expected in 1993. Hybrid (INS + GPS) automatic landing systems are being improved every day; however, we are still a long way from the CAT III specifications and it is still questionable whether CAT III will be achieved with differential GPS plus INS.
This is why development of *synthetic vision* is being actively promoted today. For performance and safety considerations it seems that microwave and infrared sensors could be used to reconstitute an image of the runway in spite of clouds, fog or haze. Probably the two systems will be used simultaneously, because with IR sensors there are always two surface temperature ambiguities : during the day the runway is normally hotter than the environment, while at night the opposite applies. Curiously, landings resemble manual landings.

## 6. TAKE-OFF MONITOR

*The take off* is performed without vertical ground references (except for the radio altimeter, which is in fact not much used in this phase) and it seems difficult to imagine a system which could give a relative position in the vertical plane with regard to an "ideal" centre line of climb referenced to the ground. This is one of the reasons why the phases "acceleration on the runway, rotation, initial climb" are still under manual control. Engine failure during these phases is crucial, and the pilot controls these flight phases efficiently. This is probably the second reason why automation of these phases is not being considered now.

Surprisingly, a number of accidents result from poor take-off configuration (Delta Airlines flight 1141, 31 August 1988, Dallas/not clearly explained yet). Even if we do not look for full automation of take-off, progress must be achieved in checking automatically the configuration given by the crew, and in blocking the throttle if the configuration is not correct.

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[9] *Some modern aircraft (A 310 and A 320) are certified CAT III "0-0". However, most airlines use CAT III A with HD (Height of Decision). At this height (15 feet under the wheels in the case of the A 320) the pilot must check the correct alignment with the runway centre line. It also exists a CAT III A with HMIA (hauteur minimale d'interruption d'atterrissage) which corresponds to a height at wich the landing can be abandonned even if an engine failure appears when the trottle is pushed; the go-around procedure is safe (no contact with the runway).*

*A comment about $V_1$* is the speed after which the aircraft, when accelerating on the runway no longer has the distance to perform emergency braking. Even if it has not yet reached $V_r$ (rotation speed) it must try to become airborne.

$V_1$ is significant only in the event of sudden engine failure. If the thrust-drag balance during acceleration is not correct, either due to a lack of thrust or abnormal drag (for example, wrong setting of the flaps), $V_1$ is meaningless! The only way to control the take-off phase is to compare the *actual* with the *nominal* acceleration, at each instant. Nominal acceleration is a function of time which involves the mass of the aircraft, the altitude of the airport...

However, such an on-board system giving a "red alarm" when the emergency braking point is passed must be reliable: airlines will not accept it until the rate of false alarm is proved less than $10^{-4}$, a rate difficult to prove as some data (MET, runway state and loading) must be manually input into the computer by the crew. Must we wait for the implementation of automatic date link and auto-control of the data stored in the computer?

## 7. THE AIRSPACE PARTITION

Sovereignty over the airspace up to 100 km in altitude is still a reality; it highlights ATC in Europe in particular way. There are 42 control centres in Europe but only 22 in the States, and that homogenous country manages 3 times as much traffic as Europe.

In the USA major airports have many runways in operation at the same time (not only parallel runways); traffic management around the airport is more complicated than in Europe. Saturation occurs more often with en-route traffic in the States, while it occurs more frequently in the TMA's in Europe; fortunately Europe has much better interconnected railway networks and short journeys (300-600 km) are often faster by train (from city-centre to city-centre).

The ICAO has recommanded a new partition of the airspace which has been globally accepted; however this new airspace division is to be implemented at the ICAO member's will.

In many countries, namely those on the oceanic seaboard which receive intercontinental traffic, bottlenecks already exist, at least during the peak season: in France six busy trunks or waypoints are recorded (Chatillon-Montmidy, Luxeuil, Montelimar, Agen, Nantes) - Besides commercial traffic, military activities (combat, training) and aircraft flight test areas interfere with each other. Discussions between military and civilian authorities seem to have solved 4 of the above-mentioned bottlenecks. One way to achieve such coordination is to specify the status of the reserved areas throughout the day. The military, as flight test training people, seem to accept such a regulation: no permanent areas (but a few exceptions) will be reserved on a 24 hour basis or with time-slots fixed once and for all. Every day the ATC will be informed continuously of the status (activate, non-activate) of the potentially reserved areas.

There is now a development gap between design (aircraft and engines) and ATC policy. Aircraft are optimized for flight levels 330-350-370, and at present 17% of commercial flights would like to use these flight levels - but only 9% can actually do so (Figure 9).

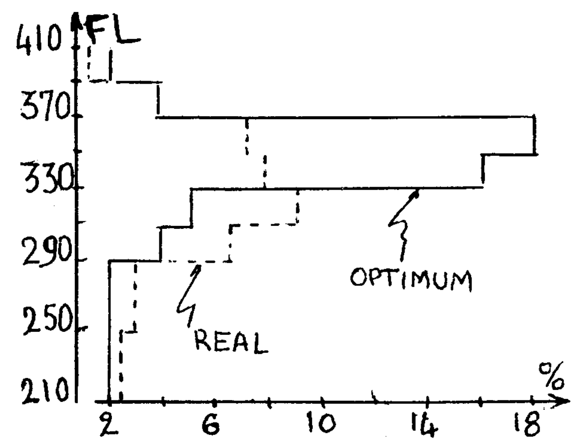


**Figure 9**

**FL occupancy**

To modify the optimum flight level for a given aircraft is a very long and costly process; its implies modifications of the engine and the air-intakes.

What must be done in the 10 years to come ? Shall we continue to use aircraft,albeit badly because very few are flying at their optimum flight level, or shall we rapidly decide to introduce a new concept on certain routes -the North Atlantic for instance - (and check it quickly): this is a train of aircraft separated by some nm instead of the 60 nm which is the rule over the Atlantic. Here we can use the diff-GPS concept.

Let us assume that a collection of aircraft having similar performances are flying the same route. If all the aircraft are equipped with digital VHF, one can be declared as the *reference aircraft*; it broadcasts its GPS lat-long-altitude[10] to the other aircraft "in the train" which navigate in relation to the reference aircraft. Obviously, many aspects of the situation must be

studied and simulated ; for example the separation distance should be determined from the case "engine failure in an aircraft" ; the "homogeneity" of the GPS signals should be checked in order to verify that the 4 satellites considered by GPS receivers in each aircraft are the same for all the aircraft in the train ; failure of one receiver in an aircraft must entail a safe procedure for the rest of the flight.

The airspace structure itself is in the process of being modified mainly with a view to simplifying procedures, increasing the number of movements at airport (landings, take-offs) and improving safety.

It may be noted that since 23 April 1784 "authorizations shall be requested and delivered before any airship quits the ground..." (French law).

At the present time IFR and VFR traffic is mixed in certain airspaces. The new airspace division specifies the rules when the traffic is mixed. Formerly, only the "look and avoid" rule was mandatory when VFR traffic used IFR airspace or even airways. Owing to the increase in traffic density, such a rule has become unsafe.

The new regulations which are gradually being implemented by the States, with the date of implementation left to their discretion, tend to give guidance to pilots, telling them "*where to look*". If the traffic in the area is only under ground control, then "*avoidance*" is still a matter for the controllers. The prevention of collisions implies standardised separation between aircraft and information about all traffic in the vicinity of each aircraft.

Airspace is now divided into 7 classes, and in each class of traffic types are specified: IFR only (class A), or IFR and VFR (all the other classes). Types of "control" or "flight information" and data appertaining to each class are given in Table 1 below. It would take too long to comment on these new regulations in detail. However, it is noteworthy that the States can decide not to use the 7 classes of airspace. For example, in France the new division of the airspace was adopted on April 1992 but classes B and C will not be implemented, at least not for a while. Class F will not be used in France.

Those interested in further details could apply to their civil aviation authority to get copies of the document concerning the new division of the airspace.

Commercial traffic normally uses airways as specified in upper airspace charts. A route is normally flown at constant flight level; its horizontal projection is a collection of straight lines joining way points. A represented way point may be located by a radiobeacon (VOR, VOR DME,...) or by an intersection of two bearings or by one bearing and a distance. En-route navigation is performed by airborne navigation equipment (INS, GPS, OMEGA receivers...). A route can terminate by an *instruction* such as "intercept ILS and stay on it".

In congested areas, routes parallel to published routes are proposed by controllers to aircraft equipped with R-NAV systems. Problems may arise at the point where routes join again.

In Terminal Areas, horizontal routes often diverge from the airport route structure; aircraft are guided by ground controllers thanks to radar location, which is called "*vectoring*". Vertical profile in a TMA is dictated by controllers.

Such are the various ways of controlling aircraft safely from origin to destination. New devices are under development and will soon be in operation : certified navigation satellite communication with the possibility of automatic position reporting, and monopulse radars with MODE S capability i.e allowing automatic data link.

In concluding this chapter, we cannot but point out the precarity of all information exchanged between the ground control station and aircraft. All data are voice data through VHF, UHF or HF; the quality is poor; the phraseology, which is supposed to be standardised, is often abandoned for free dialogue and the English language may present some difficulties for those for whom English is not their mother tongue. The operational use of an automatic data link is mandatory and urgent. In this connection reference is made to "*Recommendation* 5" issued by the French "Académie Nationale de l'Air et de l'Espace" after the International Symposium on Air Traffic Control held in Toulouse, November 1990, Document n°5 (French and English versions available) which is reproduced below :

[10] *altitude could be confirmed by the barometric altimeter (set at 1013.5 hPa).*

| Class of airspace | Permissible flights | ATC Service | FIS | Alerting Service | R/T reporting mandatory | Subject to clearance | Controlled Flight |
|---|---|---|---|---|---|---|---|
| A | IFR | Separation IFR / IFR | YES | YES | YES | YES | YES |
| B | IFR | Separation IFR / IFR IFR / VFR | YES | YES | YES | YES | YES |
| | VFR | Separation VFR / IFR VFR / VFR | YES | YES | YES | YES | YES |
| C | IFR | Separation IFR / IFR IFR / VFR | YES | YES | YES | YES | YES |
| | VFR | Separation VFR /IFR Trafic info. VFR / VFR | YES | YES | YES | YES | YES |
| D | IFR | Separation IFR /IFR Trafic info. IFR / VFR | YES | YES | YES | YES | YES |
| | VFR | Traffic info. VFR / IFR VFR / VFR | YES | YES | YES | YES | YES |
| E | IFR | Separation IFR / IFR | YES | YES | YES | YES | YES |
| | VFR | NO | YES | YES | NO | NO | NO |
| F | IFR | NO | YES advisory | YES | YES | NO | NO |
| | VFR | NO | YES | YES | NO | NO | NO |
| G | IFR | NO | YES | YES | YES | NO | NO |
| | VFR | NO | YES | YES | NO | NO | NO |
| SPECIAL CASES (CLASSES D AND E) | | | | | | | |
| **Class of airspace** | **Permissible flights** | **ATC Service** | **FIS** | **Alerting Service** | **R/T reporting mandatory** | **Subject to clearance** | **Controlled Flight** |
| D | IFR | Separation IFR /IFR IFR / VFR | YES | YES | YES | YES | YES |
| | VFR | Traffic info. VFR / IFR Traffic info. VFR / VFR | YES | YES | YES | YES | YES |
| E | IFR | Separation IFR / IFR IFR / VFR | YES | YES | YES | YES | YES |
| | VFR | Separation VFR / IFR Traffic info. VFR / VFR | YES | YES | YES | YES | YES |

**Table 1**

**The need for reliable and unambiguous ground-to-air links at an early date**

The accident rate due to ATC is relatively low. However, a large proportion of accidents are due to misunderstandings in the verbal exchanges between pilots and controllers. There are various causes: poor understanding of international aeronautical English, ambiguous phraseology, superimposition of the message on demanding tasks, poor sound quality...

The people in charge of air traffic control have made studies concerning the use of the potential of MODE S communication for ATC ground-to-air exchanges. The use of satellites for the same purpose is also being considered. Nevertheless, the benefit of such work may not be operationally available for ten years .

Likewise, but independently, private initiatives (ACARS and AIRCOM systems of ARINC and SITA organizations) have for over a decade speeded up the successful implementation, by digital-VHF and computers, of facilities for information exchange between airline pilots and ground stations. Is it not right and proper to take into account these initiatives (results and experience) in the development of systems for reliable and unambiguous communication between pilots and controllers?

The outstanding problems are still many, but, essentially, they relate to the large number of factors involved in the data transmission and processing chain between pilot and controller. Theses problems are made more complicated by inadequate coordination between the principal parties, whether they be national, public, private, professional, etc.

Ergonomic, technical, and economic studies should be organized worldwide, or at least on a European scale.

**Recommendation 5** :

Communication between pilots and controllers constitutes today the weak link in the chain of air traffic control. Future control systems, in the long and medium term, rely on the availability of automatic digital ground-to-air links (MODE S mainly in well populated areas). Pending their implementation, and in view of the success achieved by airlines in ground-to-air exchanges based on techniques of the ACARS and AIRCOM type, the Académie recommends the consideration of these results with a view to defining as rapidly as possible, with all involved parties, a type of reliable, unambiguous ground-to-air data link".

End of citation.

## 8. COMMENTS ABOUT THE FUTURE OF SST

Will the 13 Concorde flying today have successors or not? This is a controversial question which receives appoint answer every day; a lot of money is spent in the major aeronautical countries to study the feasibility of Supersonic Transport fleet(s). The NASA requested budget for aeronautical R and D for 1994, is 1 G $ among which 187.2 M $ are earmarked for high speed research, the HSCT (High Speed Civilian Transport).

The main factors entering in these studies can be listed, by order of importance, like so :

a) Chemical pollution; namely the $NO_X$ emission and its interaction with the $0_3$ layer

b) Noise perceived on ground which includes

- the noise around airports during take-off and landing
- the sonic boom.

c) The operating cost which includes the ways of operating the planes (schedules versus local times) and the ticket price.

Let us comment about these 3 factors :

Chemical pollution[11]

The interaction between $NO_X$ and $0_3$ has been proved; in the troposphere (0 to 10-12 km of height) there is a constant mixture between the various lagers and, consequently, it is hard to determine what is the part due to industrial (including ground transportation) and the part due to aircraft. In the average the $0_3$ content increases by 2% per year, over the last 24 years. However, a more detailed study shows that above 4 km there is no change during the last 10 years (1982-1992) while, as we have said previously, the air traffic experienced an increase of lying between 80% and 100%. But, it will be unfair to claim that aircraft has no influence on the $0_3$ content in the troposphere.

The European Panel which participated in the LOTOS report considered that "environmental problems will play a much more important role in the coming 25 years than is the case today". Special mention is made of the new supersonic generation (... if it materiali ses!). If the cruising speed is between Mach 3 and 4, the altitude at which the aircraft will fly falls into the region of highest ozone concentration (for mid latitudes). The interaction between $NO_x$ and $O_3$, the

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[11] *This paragraph results from a discussion with Dr André Girard, Physics Department, ONERA, France.*

effects of which are still the subject of controversy, is a real problem. Figure 10 shows the residence time of a particle deposited at different altitudes and different latitudes. At a 45° latitude a particle deposited by a subsonic aircraft (30,000 - 40,000 ft) will remain there forhours or several days; the same particle deposited at 45,000 ft will remain one month and, if deposited at 60,000 ft it will remain 0.6 year.

If damage can be proved, such aircraft will certainly never be built; at Mach 2-2.5 the optimum altitude is between 40,000 and 55,000 feet, and the $O_3$ concentration is smaller; the interaction has been studied thanks to Concorde and large-scale experiments will begin soon.

The major unknown is connected with the lightning and volcanoes. The production of $NO_x$ by lightnings is well known for a long time. Recent studies made by the "Comité Avion-Ozone" indicate that the production of $NO_x$ by lightning can be estimated between 6 and 295 MT/gear [Ref. 3]. Though the range is extremely large, it is a first indication; we can assume that, in the average, the number of lightnings is quite constant over a year. Further studies will probably reduce soon this uncertainty margin.

It is quite different for volcanoes emission or production of $NO_x$ from the ejected materials (high temperature); in the average the number of active volcanoes in the world is about 200. The recent eruption of the Pinatubo has shown that temporary interactions (1 to 3 or more years) with the troposphere - and maybe the stratosphere too - depart from "random noise" normally associated with the ensemble of volcano eruptions.

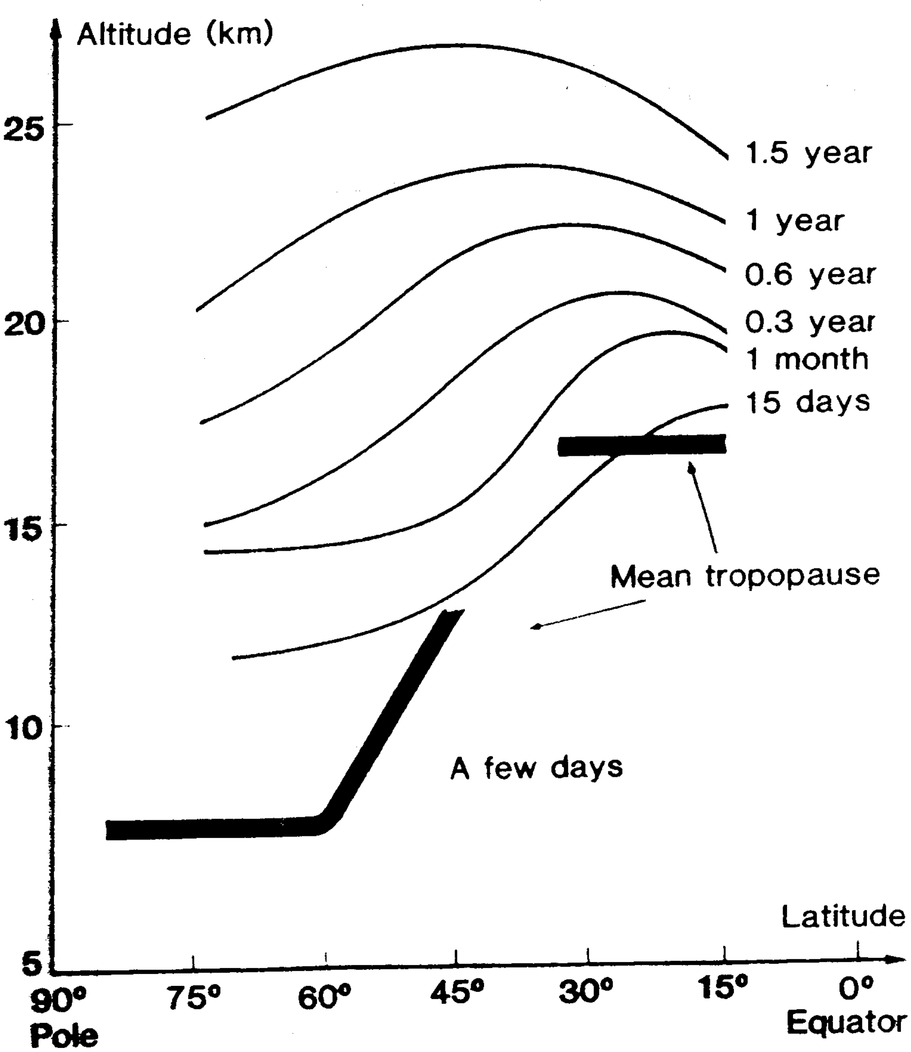


**Figure 10**

**Residence time in the atmosphere**

This brief comment shows the extreme complexity of the problem; in fact, the importance of the problem has been discovered recently (some 10 years ago) and we hardly can expect non-controversial results before the end of the century.

Nevertheless, it seems reasonable to look for low $NO_x$ emission engines, a constraints which is hard to match with high efficiency (low fuel consumption) engines.

Noise around the airport

All aircraft build today must comply with FAR Chapter 36 stage 3 ; or ICAO Annex 16, Chapter 3 ; fortunately the recommended noise levels are the same in these two documents ; however the ways to measure the noise levels in three points differs. Supersonic transport is taken into consideration in ICAO, Annex 16, Chapter 4 ; a committee (CAEP Committee for Aviation Environmental Protection) under ICAO has set up 4 working groups to study the future reglementation. At last, the DGXI of the CEC is studding the possibility of reducing by 3dB the noise in each of the 3 reference points.

At the present time, it is thought that no derogation will be accepted for supersonic aircraft.

The question of supersonic aircraft noise arises mainly at the time of take-off when using afterburner, during sonic acceleration and the performance of manoeuvres (noise focalisation). The currently unavoidable "noise footprint" that occurs when an aircraft is flying supersonically has been rejected by 52 countries worldwide. Will supersonic aircraft, therefore, be allowed to fly at supersonic speed only above oceans (as is the case for Concorde)? With regard to the noise generated during the climb (the current limit is 85 dBA), it is expected that new engines will allow a much steeper climb and that the 85 dBA footprint will be potentially smaller than that of subsonic aircraft [Ref. 4].

The main cause of noise is the velocity of the exhaust gaz; to satisfy the regulation, the exhaust velocity should be kept smaller than 390 m/s. The exhaust velocity of the Concorde's Olympus engine is 900 m/s. Then, it is obvious that only high by-pass engine may compete with the regulation and its efficiency must be as good as the pure turbojet, like those of Concorde, a difficult problem to solve. SNECMA and Rolls-Royce are studying a high-airflow variable-cycle engine ("mid tandem-fan"); it uses an auxiliary fan wrapped around the mid section of the compressor; it is driven by the low pressure turbine.

Furthermore, it seems likely that a stage 4 of FAR 36 will come up before end of the century and limit a little more the noise perceived in the vicinity of the airport ...

Noise due to the sonic boom

It is very hard to act on the footprint of the sonic boom without degrading the aerodynamic performances of the aircraft. To reduce the pressure discontinuity felt on the ground it is mandatory to increase the sweep angle of the front ledge of the wing, which induces a larger root-chord. Here again a compromise should be looked for between the $\Delta p$ steepness of the front edge of the pressure variation ($\Delta p$) on the ground and the efficiency of the aircraft (total mass over paying mass).

However, more attention should be put on the guidance of the plane to avoid any sonic wave focalization over populated areas. The focalization arises when the plane accelerate (or decelerate) and/or when the plane makes a turn. If, normally, a $\Delta p$ of 2 to 5 hPa is considered as acceptable for a non-accelerating plane, $\Delta p$'s of 5 to 8 hPa may be encountered when the plane evolves. Such pressure discontinuities are unacceptable.

Operating cost

In spite of these severe constraints (low $NO_x$ emission, high efficiency, low exhaust velocity, controlled sonic boom) it is thought that there is a potential market for a supersonic transport fleet of a few hundreds aircraft all over the world if the sailing price of the ticket does not exceed by 30% the price of the economy class equivalent ticket (on subsonic aircraft). This is a challenge which leads to further studies as to the success of that type of aircraft.

## 9. THE MAN IN THE LOOP

### 9.1 General comments about automation

Automatic control theory really began during the Second World War. Norbert Weiner developed this new discipline (he was a professor at MIT). We are all aware of the tremendous achievements made 30 or 40 years later.

However, the scientists who worked in this field, at least during the first 30 years (1940-1970), considered it an "exact science" and their leitmotif might be summarized as follows: "automate the time-consuming, unhealthy, or dangerous tasks, and man kind will be happy".

For the last fifteen to twenty years, we have known that this is an erroneous goal. Two reasons for this are as follows :

- in many systems, man is still "in the loop" as an

"operator". This is obviously the case with aeronautics both on board and on the ground (ATC controller) ;

- even if a "system" is fully automatic like a satellite launcher (it becomes fully automatic only a few minutes or seconds *before take-off*), the operator only has the possibility of destroying the launcher if something appears to be wrong. This system is surrounded by systems which are not fully automatic and human operators control them.

An ideal, completely isolated automatic system is extremely rare or non-existent. Thus man is *in the loop*, and this must be taken into account as well as the physical components. It is a much more difficult problem than those on the engineering side!

We propose calling any system where man is involved in its control a *semi-automatic system.*

We would define a semi-automatic system as follows:

a) *Inside the system's specification set*, it may be in automatic or manual mode, as selected by the operator. The transition from manual to automatic and vice versa must be continuous (smooth). The manual mode may be partially automated.

b) *Outside the specification set*, two situations are possible:

- a *declared failure situation*, i.e. a situation where an alarm is registered; again, two scenarios are possible :

  . the system switches to a downgraded mode (the operator is supposed to be informed) ;
  . the system is automatically turned off and manual mode is mandatory.

- an *unexpected system status*. In this situation, no declared failure is registered, and the operator should take decisions.

We will now define "failure" and "unexpected system status" more precisely.

A *failure* is a on-off event in time occurring at random. It begins with the break-down of a component, i.e. the component is no longer within its design specifications. The break-down may be unobservable on its own but it causes an *observable failure* or a *symptom* at a sub-system level. A symptom is an observable event which does not belong to the class of expected events: it could be a positively *incorrect indication* such as aerodynamic speed equal to zero when in flight, or *abnormal* vibration of a wing, called "buffeting", or very often a combination of such events.[12]

Such a definition means that the specifications of a component and the matching of the specifications of all components, i.e. the overall specifications of the system, must be consistent and cover the *whole set of admissible inputs.*

*A failure always has a known cause which is known, estimated or unknown*[13].

Symptoms appear after a failure but do not allow direct identification of the failure ; they present a graph of possible failures.

An "*unexpected system status*" is more difficult to define. Such a status may arise after a failure, where the failure is *not identified* (no symptom). We will not be discussing such cases. It may also arise where there is no failure, either real or hidden. Component specifications at the lowest level and subsystem (SBS) specifications at a higher level are always defined in terms of ranges (for example: input power supply voltage 5 V ± 0,5 V). Where there are many components in a SBS, the SBS outputs may appear abnormal, i.e. no longer fall within the nominal range, even though there is no on-board fault. Moreover, even if the components are correctly set within the accepted range of accuracy, the concurrence of certain input vector values could lead to an unexpected output vector, in agreement with the SBS's logical and mathematical models.

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[12] *This may result from combinations of the load factor, the speed, the altitude and the temperature of the atmosphere. Normally if a failure has occurred in one of the computers responsible for maintaining the plane within the "flight envelope", which is "flutter-free", it is detected and automatic reconfiguration is performed.*

[13] *The satellite Telecom 1-B is non-functional owing to a fault in one component, a power diode, which appeared for the first time 2 years earlier. If this diode had clearly failed when the first fault was recorded (21.2.86), it could have been disconnected and replaced with a spare circuit by remote control, and the satellite would still be operational today.*

Survivability after failure

As already stated, failure is an event in time or a random sequence of occurrences, and is generally known only by its mean values. In either case the evolution of the system will depart from the nominal. This evolution is a fundamental factor with regard to safety, pilots have to control the aircraft in spite of the failure and controllers have to take unexpected decisions in order to maintain separation between planes, even after an incident.

Let us take an example. In paragraph 2 we said that twin-engined aircraft are authorised to fly over the Atlantic (or any sea) subject to certain constraints: the manufacturer has to define how the aircraft can be flown after one engine has failed and must prove that the probability of crash is still of the order of $10^{-8}$ per hour for the remaining flight.

Modelling of the operator

The design of a semi-automatic system entails the modelling of the operator, a task which is quite impossible today, though many approximate models are often used. The envisaged qualification of the operator must be carefully defined prior to the computation of the system and taken into account during the design of the whole system[14].

Once the qualification is specified, the operator's deficiencies, in relation to the standard profile, must be estimated. Let us take, as an example, the pilot-induced-oscillations (PIO) of a manually controlled aircraft in the approach phase for an aircraft with a low (but positive) stability margin. Some good and qualified pilots may experience oscillations around the prescribed trajectory, whereas no oscillation would occur if they had abandoned the controls, the plane being initially well stabilized. The oscillations result from the "out-of-phase" commands given by the pilot and they remain quite stationary. At the present, time it is not possible to model such a process, i.e. make a model that would correspond to correct control at any point of the flight envelope and that would lead to PIO in certain approaches.

In conclusion, it is clear that an aircraft, like a controller, is a semi-automatic system ; these two semi-automatic systems are closely linked, making their study *additionally complex*, because psychology and human interactions are involved.

### 9.2 Present state of ATC

In concluding this chapter, we would stress the extreme variety of flight profiles for modern aircraft ; against these ATC rules appear to be very limited: route configurations, vertical separation, constant FL, separations set independently of the aircraft type etc...

As we have seen, the entire flight of a modern aircraft can be performed in an automatic mode, at least in the airborne phase just after take-off up to - and including - the braking phase on landing: this is a technology-driven problem... However, a flight could be performed in a fully automatic manner only if the aircraft did not experience any conflict with other aircraft, or only minor conflicts which could be detected some minutes in advance. A fully automatic flight would imply automatic ATC, a tremendously difficult problem. It is optimization of a multi-agent problem which implies the specification of a criterion or criteria. Chapter 8 is devoted to the choice of a criterion.

Besides these major differences between technology-driven problems and management problems, human intelligence should be considered mainly in terms of its ability to process qualitative data, a function that processors do not perform well today (except in laboratories: "fuzzy logic"). Apprehension of a situation, for example a potential conflict between two aircraft in a congested environment, is quite easy and fast for the human brain, while it is hard to acquire by a computer .

Correlation operations which approximately evaluate the similarity (distance in the mathematical sense) between two phenomena, whether static (similarity between scenes) or dynamic (similarity between functions), are performed by the human brain in relatively precise ways, whereas they necessitate very long calculation on computers.

## 10. AUTOMATION TRENDS

Is full automation possible? Georges Maignan, Director of the EUROCONTROL Experimental Centre at Brétigny tried to answer this question in his paper "Towards a global Air Traffic Management System", presented at the AGARD symposium in May 1993. On the basis of the fact that there were 2 million IFR movements in Europe in 1972 and 4,46 million in 1992, he noted that the air traffic management fol-

[14] *Had a high level nuclear scientist been present at the Chernobyl plant, the accident would not have occurred (Xenon production when the reactor operates below 50% of its nominal power)! The knowledge of the operator must be taken into account in order to define the kind of automatic constraints to be implemented in the equipment.*

lowed traffic demand but only "reluctantly" [Ref. 5]. In the 1980s, great hope were pinned on CNS, a satellite-based architecture for Communication, Navigation and Surveillance. In 1991, the ICAO Council acknowledged the work performed by the FANS (Future Air Navigation System) working group. The bottlenecks are not in fact communication, navigation and surveillance, they are runway capacity and unit sector capacity. We will come back to these problems (ground movement of aircraft, and wake vortices during final approach and initial climb and during movements on the runway) in a chapter devoted to "The airport of the future (and its TMA)" (chapter 10). Georges Maignan subsequently considered sector capacity. It is poorly used, both because of present separation regulations and because of the random environment in which aircraft fly. Controllers cannot remember the actions they have to perform in order to maintain, conflict-free, a fleet of 50 to 60 aircraft simultaneously, and he concludes by saying that "the controller needs more automation to help him in the tasks at which he is good and to replace him in those at which he is not".

The R and D effort should be multidisciplinary and integrate airborne and ground research, a difficult problem owing to the diversity of countries involved, namely in Europe.

The European programmes are federated by PHARE (Programme for Harmonised Air Traffic Management Research in EUROCONTROL). The electronic aids to the controllers are part of DMA (Decision Making Aids), which is itself a part of EATCHIP (European ATC Harmonisation and Integration Programme).

## 11. LANGUAGE AMBIGUITIES

If no action is taken along the lines suggested above, i.e. to consider the problem as a whole, affecting both ground controllers and flight crew, conflicts may soon proliferate.

In 1990, the Académie Nationale de l'Air et de l'Espace (ANAE), located in Toulouse, produced a document entitled "Recommandations", following its symposium devoted to air traffic management. It was noted that there is no cross-fertilisation between engineers developing the "glass cockpit" and those developing electronic aids for controllers.

"Man-machine" communication has many common facets : data presentation, particularly in stress situations (e.g. an incident on board or temporary overload on the ground), acknowledgement of instructions given by a scope (on board) or by VHF (on board, on the ground), rate of data refreshment. The most important is probably "man-man" communication : there are two or three men on board, and two or three men at a sector control position.

Psychologists ought to be increasingly involved in these studies.

We have already referred to the *additional complexity* in studies of semi-automatic problems (aircraft, ground control) caused by the linking of these two systems. Future traffic growth will entail the development of new air traffic management systems by teams from the aircraft manufacturers, the airline operators and the air traffic control authorities, if conflicts are to be avoided.

Let us hope that cooperation will soon become a reality. Following studies performed at Aeroformation, Toulouse, a paper was presented at the ICAO meeting in Washington in April 1993 on "Pilot strategies of crew coordination in advanced glass cockpits: some effects of expertise and culture" [Ref. 6]. This paper points out that crew coordination in advanced glass cockpits calls for two types of synchronisation : temporal synchronisation for actions, and cognitive synchronisation for situation awareness. Communication between crew-members and with systems is considered as the key domain for insuring these two kinds of synchronisation; the paper did not hesitate to mention "social factors in the success of communications in glass cockpits", technical system knowledge, procedural communication knowledge (skill in making call-outs, briefings, checklists), and the importance of fluency in English.

To comment briefly on this last remark, it is well known that in high stress situations, the dialogue between two "operators" having the same mother tongue, switches from English to the mother tongue. This happened in the case of the collision above Zagreb of a Trident and a DC9 (Sept 1976). Fearing a collision, the controller, a Yugoslav, knowing that the climbing aircraft was piloted by a Yugoslav crew switched to Serbo-croat to request an immediate level-off. The crew of the other plane, who were British, did not understand the messages and were not aware of a threatening danger. Would the facts have been different if the dialogue had continued in English? Certain similar situations, fortunately encountered on training simulators at Aeroformation, are mentioned in the paper mentionned in Ref. 6.

We cannot ignore the difficulties arising from the growth of English at international level. Even between operators having the same mother tongue, the interpretation of instructions or requests may be difficult (cf. the Tenerife accident: a collision between two planes on the ground, one landing, the other taking off ; more than 500 people killed). This may be due to the poor quality of the VHF link or to a departure from official phraseology. Nevertheless, certain situations may

require the use of non-standard phraseology.

The so much expected automatic data link will solve the problem, partly because the interpretation of the meaning of the message will still be different for operators who have English as a mother tongue and those who do not. In addition, it takes longer to read a message than to hear it; if quick answers (acknowledgment or reply message) are requested some "macroscopic" delays, of the order of 2.5 to 12 seconds, may occur when radar SSR-Mode S data links are used.

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# CHAPTER 3

TRAFFIC EVOLUTION

# TRAFFIC EVOLUTION

by

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## 1. WORLDWIDE TRAFFIC

After a long period of regular increase at an annual rate of between 4 and 4.5%, air transport was hit by a sudden and unexpected crisis just before the Gulf war, resulting in an average aircraft load factor of less than 60% worldwide. Recently the load factor has risen because of a ticket price war, but this seems to be an unstable and temporary situation.

In 1990 a study[1] commissioned by EEC/DG XII [Ref. 1] accepted a worldwide growth rate of 2.7% to 2.9% for economic activity. Air transport demand was estimated to rise by 4.5% per year - implying an almost threefold increase in air transport demand in the next 25 years - while cargo traffic was expected to grow by about 8% per year.

A EUROCONTROL report entitled "Time-based Air Traffic Control in an Extended Terminal Area" [Ref. 2] a summary of the expected rate of growth as perceived by the Organisation was given : average annual passengers growth evaluated at 6% in Europe with a peak at 10% around 1999. At such a rate the number of passengers would double by the year 2000 and triple by 2010. From the ICAO journals (June 1991 and June 1992) a *decline* of 5% arose between 1991 and 1990. The quite regular growth from 1983 to 1990, at a rate of 15 pax-km per year (about 7 to 8%) was broken during 1991 and the number of pax-km in 1991 was about the same as the one in 1989 (gulf war) Figure 1.

The rate of growth of freight was quite linear between 1985 and 1990 (about 12%) but suffered the same decrease during 1991 Figure 2.

The rate of growth of mail (Figure 3) followed about the same pattern still from the ICAO journals the number of aircraft movements is given in Figure 4 for the two most loaded airport of the Western Europe (London-Heathrow and Frankfurt).

The present economic crisis makes any forecast quite unrealistic; only similarity with the past may incite to accept for a 10 year 1929 crisis period a rate of growth close to the smallest figures mentionned in the above document, i.e. a rate of growth 4% for passenger-km and a rate of 7% for freight (tonne-km).

If we take into account that some aircraft for domestic traffic or short distance traffic - let say between 700 and 2000 km - are becoming larger and larger (a cooperative project for a 600-800 passenger traffic exists at the present time), the accepted rates of growth will lead to doubling the aircraft movements around year 2008 ± 2 and tripling it around 2015-2020.

After 2010 the market will be a replacement rather then a supplier's market: the rate of growth will certainly drop by 0.5% or 1%, and later by 2 to 3%. Another factor will operate in the same direction: the "guaranteed" aircraft life, which was 30,000 flight hours until recently, has now increased to 35,000 hours, and 40,000 hours are expected in the case of aircraft built in the years 2000-2010.

Short-haul traffic is expected to decrease *at least in Europe* and in some other congested parts of the world owing to the rapid development of rail and highway networks. Scheduled traffic between cities 400 km apart will gradually disappear over the next 15 years.

[1] *The LOTOS panel report, DOC. EUR. 13334 EN, issued in January 1991.*

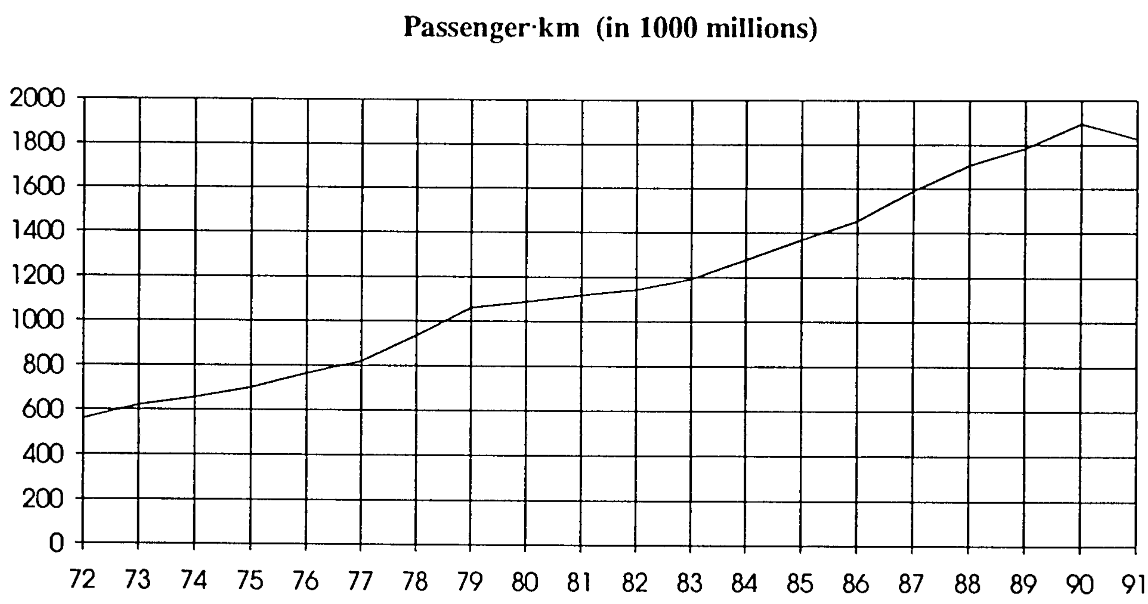


**Figure 1**

**Passenger-km traffic evolution**

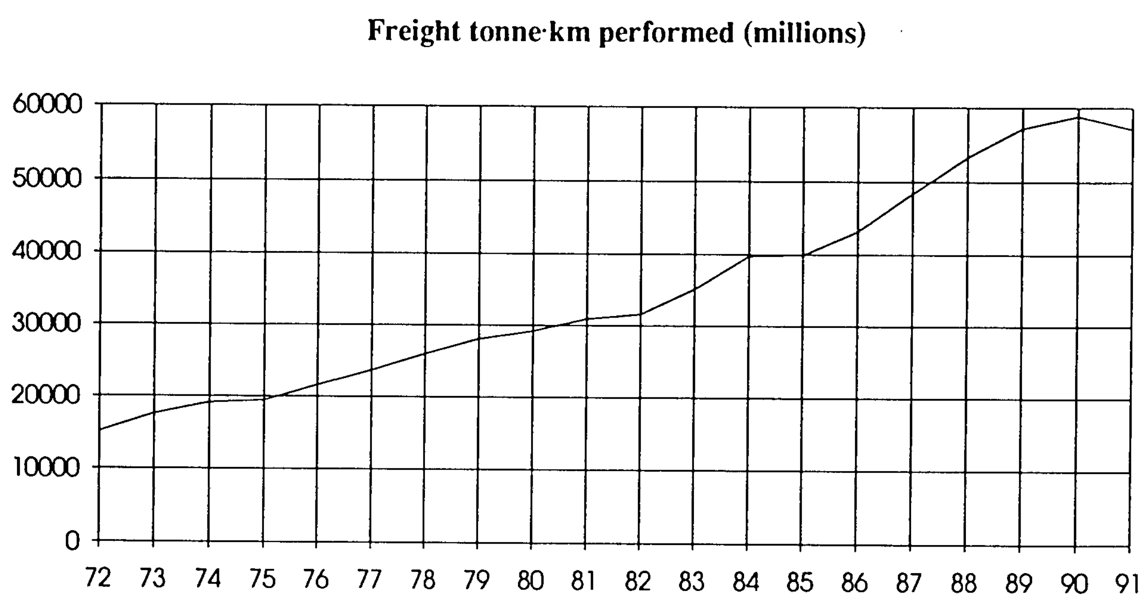


**Figure 2**

**Freight traffic evolution**

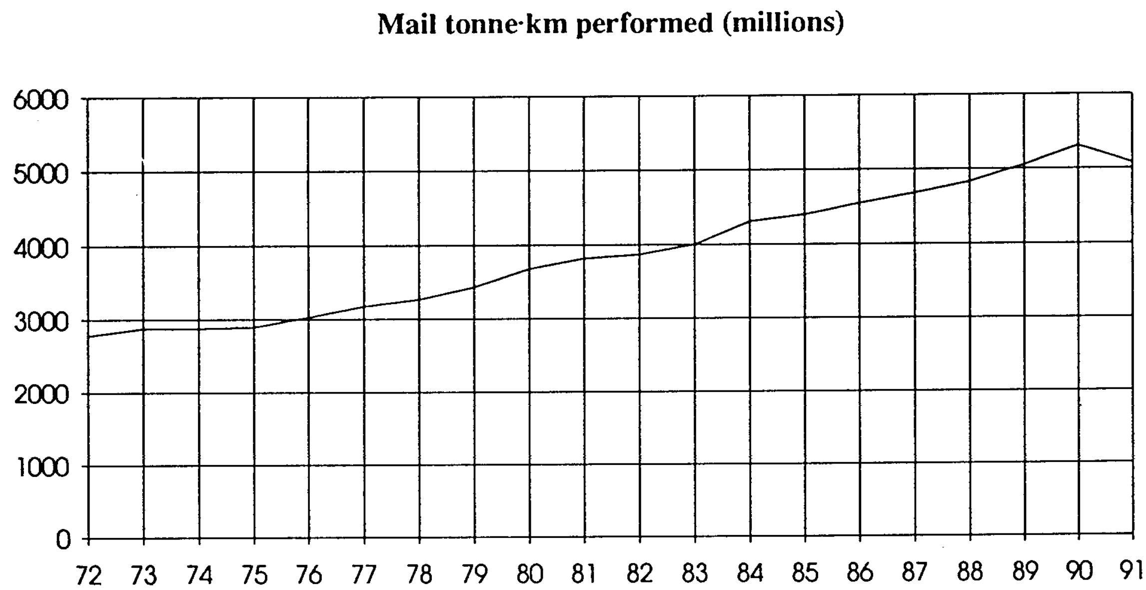


**Figure 3**

**Mail traffic evolution**

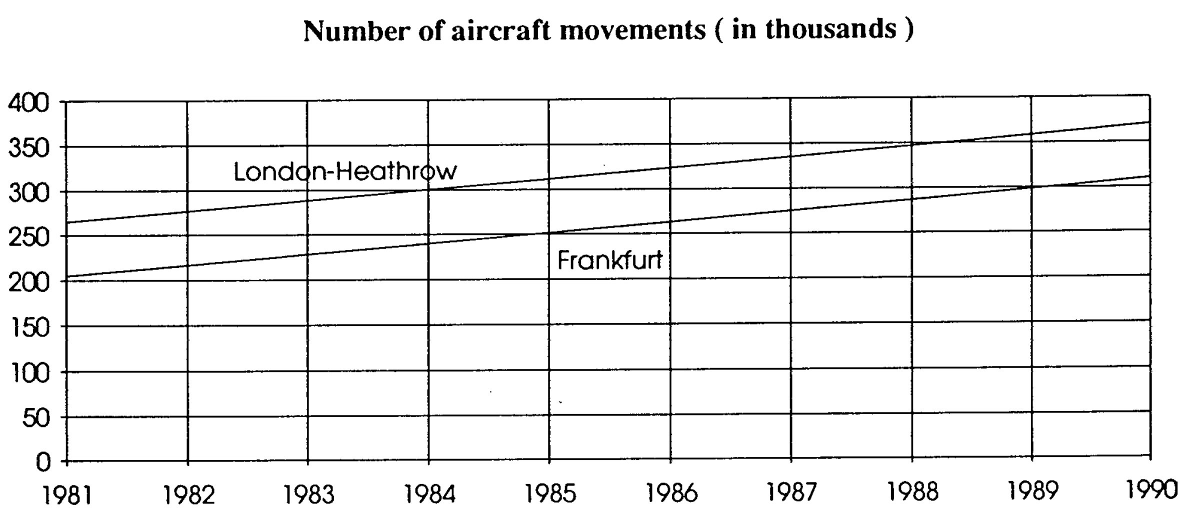


**Figure 4**

**Number of aircraft movement**

Moreover, the rapid introduction of high-speed trains (TGV) suggests that air services between cities 400-700 km or more apart will no longer be available either. However, acceptable transversal accelerations for high-speed trains limit the radius of curvature of the track on both the horizontal and vertical planes; hence, where there are mountains between cities, the cost of the track may be too high and TGV links may be abandoned.

The present situation is overwhelming and difficult to explain - the economic crisis has direct consequences for air traffic; however, though the number of commercial flights fell in 1991 (Gulf war) and 1992, the total number of passengers carried in 1992 increased slightly owing to increased numbers of holidaymakers. For the airlines this is a tremendous loss of money because this new category of passengers is using economy class and not business or first class. In addition, as a consequence of deregulation in the United States, which has now spread to all other countries, fares have been reduced drastically by the large airlines: in doing so, they hope that small airlines, forced to reduce their fares to the same extent, will not survive... and large airlines will buy them up cheap!

Another factor, closely related to the previous one, is the number of aircraft which are at present "grounded": roughly 10% of the fleet. Table 1 gives the number of grounded aircraft in June 1992 and May 1993. The 3rd column indicates the percentage of the total number of aircraft per type as of May 1993.

In the case of US airlines the number of grounded aircraft jumped by 31% in a single year (802 aircraft in June 92; 1,049 in May 1993). IATA claimed that this number will continue to rise and that there will soon be some 1500 grounded aircraft. Most of the grounded aircraft are old (70% are more than 15 years old); however, some brand new aircraft acquired recently by an airline have been grounded ... before their intended flight.

| Number of aircraft grounded | June 1992 | May 1993 | % of the total fleet by aircraft type |
|---|---|---|---|
| A300 | 27 | 42 | 10,9 % |
| A310 | 12 | 20 | 8,7 % |
| A320 | 0 | 5 | 1,3 % |
| Bac 146 | 36 | 53 | 24,3 % |
| B707 | 45 | 59 | 14,2 % |
| B727 | 206 | 274 | 16,2 % |
| B737 | 81 | 134 | 5,7 % |
| B747 | 46 | 59 | 6,3 % |
| B757 | 14 | 20 | 3,7 % |
| B767 | 1 | 1 | 0,2 % |
| Fokker 100 | 24 | 23 | 12,3 % |
| Tristan | 22 | 38 | 15,8 % |
| DC9 | 111 | 127 | 14,1 % |
| MD80 | 23 | 30 | 2,8 % |
| DC10 | 9 | 16 | 3,7 % |
| MD11 | 0 | 7 | 8,5 % |
| Others | 145 | 141 | |
| Total | 802 | 1,049 | 9,28 % |

**Table 1 : Grounded aircraft**

Let us now consider the major factors affecting air transport development [see paragraph 8 for supersonic transport].

a) noise restrictions will have repercussions on the development of new aircraft and their use. Noise pollution in the vicinity of airports is defined by ICAO, Annex 16, Chapter 3; in some countries, restrictions around airports are more severe.

b) Emissions (exhaust) from aircraft engines are potentially harmful additives to the atmosphere.

Aviation consumes 13% of the total fuel consumed in transport worldwide; the fact that a substantial amount of this fuel is burnt at the tropopause level or higher may create problems ($CO_2$ $NO_x$ and $NO_y$).

In consequence, new restrictions may be put on ATC in order, for example, to limit the number of aircraft per day at each FL (above FL 350). Supersonic aircraft would then be fully concerned.

c) airport extensions (additional runways) are very limited in Europe (environmental constraints). In many large cities the only possibility is to build a new airport from scratch at a considerable distance from populated areas (this is the case of the new Munich airport).

The main task for the near future is to make optimum use of airport capacity (landings and takes-offs). Two improvements would be :

- optimum delivery of aircraft to the entry gates to coincide with take-off
- optimum time slot allocation combined with reasonable distribution of flights (agreements between airlines).

Studies on airports have also examined the question of connections between airports and towns, even distant towns (up to 300 km), which would be catered for by fast trains. It is for this reason that an entire chapter (Chapter 10) has been devoted to the "Airport of the Future": airports should be considered as a whole, because any action taken in one component of the airport system has consequences for the other components. Only an overall approach will result in airports capable of coping with the traffic expected within the next 15 years.

d) coming back to the second-generation supersonic aircraft, it is clear that their integration into ATC will (... or would) imply precise algorithms in order to avoid any "holding patterns". At the present time, the only supersonic civilian aircraft are the 13 Concordes, of which no more that 2 or 3 fly concurrently; their routes and schedules are different, their time slots are known 12 hours in advance, wind interaction is much smaller than in the case of subsonic aircraft, thus making them easy to manage.

If the second generation finally arrives, there will be some 300 - 500 aircraft to monitor (this means that, at a given time 60 to 100 aircraft may be flying, some of them on the same routes and on tight schedules. If the ascent cruise, accepted today in the case of Concorde and an optimum solution, continues to be accepted, it will entail precise aircraft guidance. Fortunately, new technology, such as the Automatic Data Reporting System (ADRS) will soon be operational (in any case, before the second supersonic generation appears).

As it is inconceivable that priority be given to supersonic aircraft, with regard to subsonic ones the relative importance of delays around airports penalises supersonic aircraft much more than subsonic aircraft on an airport-to-airport flight. "Linear waiting", which consists in requesting an aircraft to pass from supersonic cruise to subsonic cruise at a given time or position, seems to be the only possibility of managing a mixed fleet of subsonic and supersonic aircraft. However, if we move towards global Air Traffic Management, it seems that only global penalisation criteria would solve the problem. In that case, agreements should be signed between airlines which operate supersonic aircraft and those which do not. (See Chapter 8).

e) every large capacity aircraft (600 - 800 passengers) are being studied by the two largest manufacturers in the world. The size has been determined by basic airport requirements, namely runway, taxiway and platform configurations; the gate systems - if any - would require modification. For example, if an aircraft has two decks, each deck should have its own gate, thus entailing a total of 4 or 6 gates per aircraft.

Many other problems require to be solved in order to handle so many passengers in about the same amount of time as is required today to handle 400 passengers arriving on one aircraft. The advent of such large aircraft will again raise the problem of priorities: what will be the rule when saturation is reached? Do we ignore aircraft capacity and organise traffic in such a way as to achieve minimum total waiting time for the *aircraft* concerned, or do we minimise total waiting time in respect of all *passengers* in the sky? This is an ongoing problem, which will be increased by the advent of very large capacity aircraft.

f) A word about cargo: its growth rate of about 8% per year is being sustained despite the current economic crisis. In tonne-km air-mail represents about 9% of the total (Figure 3). However, it seems that the growth rate for mail is lower than that for goods, and that this trend will be maintained in the future. The "quick-change" aircraft, i.e. aircraft which carry passengers during the day (domestic traffic) and mail at night, is an interesting experiment; the "change", i.e. the removal or rearrangement of seats, is carried out on small carriers (50-100 seats) within 45 to 60 mn.

In the future, it will be necessary either to monitor

both the cargo and passenger areas at airports or to specialize airports to cargo. They both give rise to similar problems: docking (the equivalent of gates), services, connecting containers or goods, connection to railways. However, some problems, such as temporary storage (sometimes cold storage) are specific to cargo transport.

Another problem in the future will be the necessity of using night slots in order to reserve daytime slots for passengers. In that case, it will be mandatory to have silent cargo aircraft at take-off and landing.

Lastly, it should be borne in mind that all the new developments, either in respect of aircraft or ATC, should not have the effect of lowering current safety levels. Furthermore, despite the constant level of the overall safety of the Air Traffic Transport System, it is easy to prove that ATC should be upgraded as far as its own safety level is concerned; curiously it is due to the media... : on current assumptions, about one mid-air collision occurs every three years (USA + Europe). In the event of a twofold increase in traffic within the next ten years, and for the same safety level of the ATC, there will be certainly more than twice as many mid-air collisions as there are now: let us say three in three years, or an average of one a year. This will not be accepted by the media, although the probability of accident per passenger remains unchanged!

## 2. EUROPEAN SCENE

In this paper we shall consider merely the North-West Europe zone, which is a "uniformly dense zone" incorporating the following cities and their airport or airports: Amsterdam, Brussels, Frankfurt, London, Paris. Figure 5 shows the structure of the upper air-space routes.

The characteristics of this zone can be summarized thus:

- weather conditions in winter are on average worse than in other zones of the same size and similar traffic density; the prevailing winds are west winds which are often saturated by humidity; the difference between the "temperature" and the "dew point" is often 1 or 2°C: fog or haze may appear very rapidly and stay for hours, sometimes for days.

  This is probably the main reason why Europe is better equipped in landing aids, mainly ILS CAT III, than the United States.

- traffic over some legs is often close to saturation or saturated all around the year. However, in Europe the holiday period is concentrated in 2 months, July and August, and many people travel from North to South (Italy, Greece, Spain ...); even now delays of up to 3 or even 6 hours can be experienced every year on some trunks.

- on the other hand, Europe is well equipped with highways and railways; high speed trains (TGV) are developing rapidly. A changeover from air to train travel in respect of distances up to 500-600 km is in progress. Air Inter, the main domestic airline in France, lost more than 50% of its passengers on the Paris-Lyon connection after the TGV went into service in (Sept. 1983), and 30% on the Paris-Bordeaux connection after the TGV went into service in (1989). Air traffic is expected to disappear completely in the case of cities within a 200-400 km radius before the year 2000, while it will probably continue to exist and may be developed in the case of cities situated within a 300-800 km radius.

In order to give an idea of the complexity of a real route network, Figure 5 shows the route structure of the North West Europe area in which the 5 major cities with their airport or airports are considered.

| | |
|---|---|
| London Gatewick - | Heathrow - City |
| Brussels | Zaventem |
| Amsterdam | Schiphol |
| Frankfort | |
| Paris Roissy - | Orly |

The routes are the interconnecting routes plus the crossing traffic throughout the area.

Aircraft normally enter the Terminal Area at specified points and at a requested altitude. In the case of departure, they normally reach an airport exit point (located within 10 to 20 nm from the airport) and then reach a "way point" located on the main route structure.

Detailed information on dayly traffic is currently available at EUROCONTROL (Statistics Services, Control Flow Management Unit). As an example, documents issued dayly include the following data summarized in 7 columns:

- countries overflown by the flight (18 binary bits)
- month of the year and the date of the day
- departure airport
- arrival airport
- aircraft type
- nature of flights : military or civilian
- airline identification

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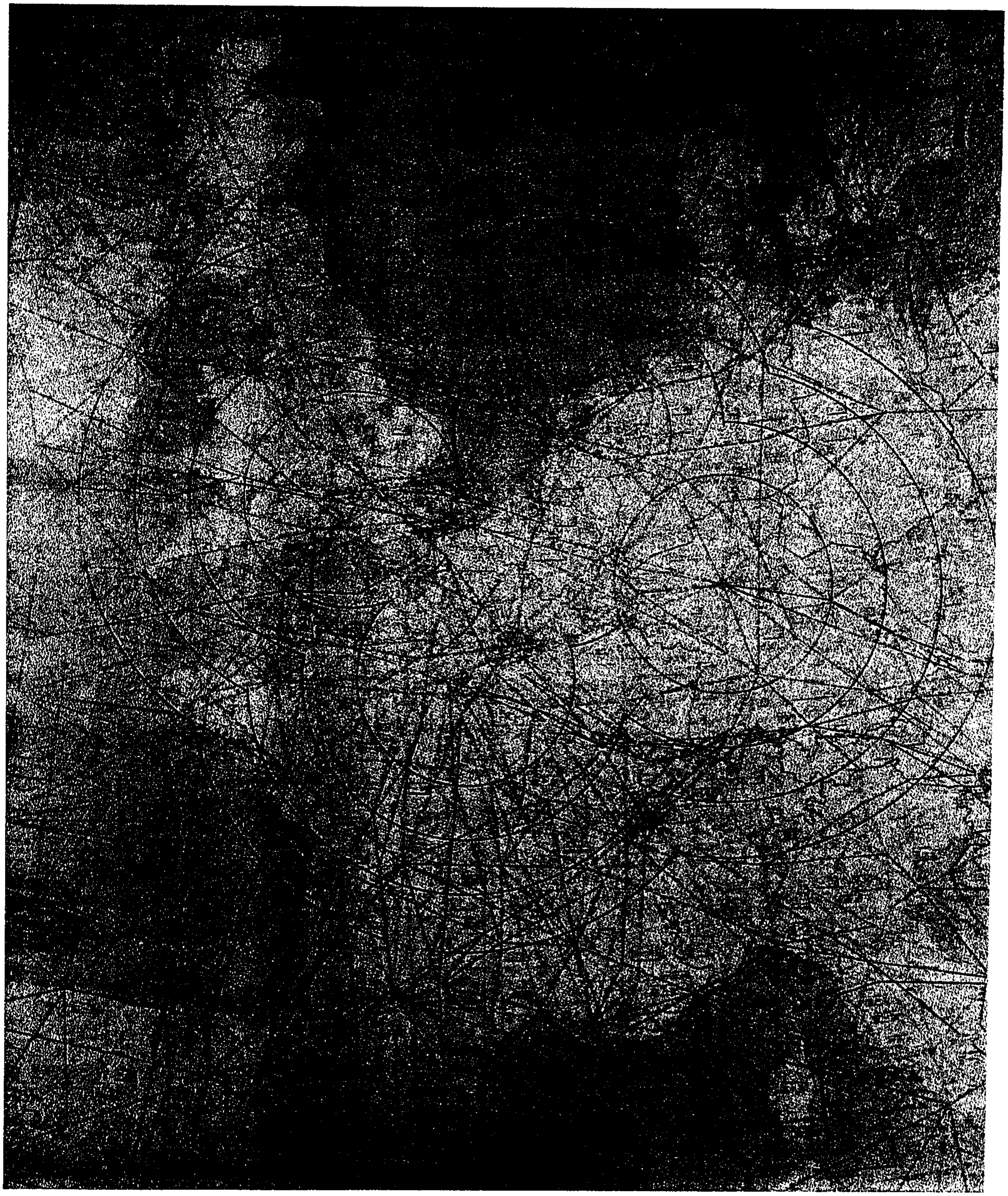

**Figure 5**
**NW Europe route structure**

# CHAPTER 4

## ELECTRONIC AIDS TO CONTROLLERS

# ELECTRONIC AIDS TO CONTROLLERS

by

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## 1. PRESENT SITUATION[1]

Nowadays controllers are aided by computers; what they have on their screen is not radar video but synthetic data coming from a processor (the "*best*" estimated position and certain data concerning individual flights, at least flight identification and FL or altitude). En-route as well as approach controllers have automatic conflict detection, which gives warning if a conflict is liable to occur within 2 or 3 minutes.

In most high-density traffic areas in western Europe and USA, flight plans and radar data are currently processed by computers (CANAC in Belgium, CAUTRA in France, DERD in Germany, FDPS in Great Britain, SARP in Holland, MADAP at Maastricht for EUROCONTROL, EARTS and ARTS in US). However, traffic flow harmonisation as a factor in optimization is much less developed; only Terminal Area Control, sometimes extended to a greater area around the Terminal Manoeuvering Area, uses electronic aids for controllers.

Three systems are currently in operation :

- the Dutch ASA system, which serves both Schiphol approach and area control (1981);
- the German COMPAS system, in use at Frankfurt since 1989;
- the French MAESTRO system, in use at Orly since 1989 and now at Roissy.

Other systems still under development or at the experimental level, include :

- the EUROCONTROL ZOC (Zone of Convergence) project now extended to cover both terminal and en-route components;
- the U.K. system PACTAS (Prediction Approach Control Tactical Advisory System);
- the U.S. systems developed under the TAAS (Terminal Advanced Automation System), under NASA/Ames: CTAS (Centre/Track Automation System), under NASA/Langley, TIMER (Traffic Intelligence for the Management of Efficient Runway Scheduling).

In these systems scheduling or re-scheduling on the controller's initiative is derived by computer and presented on a screen. The controller may request changes either in the times of arrival or, if not sufficient, in the aircraft sequencing. Very often these modifications are made by means of a pointer (or a mouse) and appear on the screen directly. The computer has rough mathematical models of the aircraft or, more often, tables of performance according to the altitude and mass of the aircraft when it enters the TMA control. Hence the computer may reject a controller's request for a modification in the times of arrival at the final beacon close the ILS capture, or in the sequencing, if the manoeuvres to be executed do not fit with the models or the company rules. The controller should devise alternative sequencing.

Details concerning the systems mentioned above may be found in the EUROCONTROL report already mentioned [Ref. 2]. From a recent visit to NASA/Ames (June 1992) the present status of CTAs would seem to be as follows:

---

[1] *Most of the data in this section are extracted from a EUROCONTROL Report [Ref. 2] and from visits to NASA/AMES, MIT and LINCOLN LAB, in June 1992.*

CTAS has been under development at Denver (Colorado) since September 1991; it is not operational, and still in a test phase; it covers an area which corresponds roughly to 45 mn of flight prior to arrival; it manages the traffic to secondary airports around Denver too, and takes transit traffic into account.

For the record, all synthetic plots collected by all radars in the USA are sent to the National Flow Control Facility located in Washington. Data are refreshed every 5 mn. The 23 control centres in the United States have access to these files. This is the ATMS (Advanced Traffic Management System).

Denver Control may know the landing sequences within the next 1 or 2 hours with an accuracy of 1 to 5 mn in the case of aircraft already in flight (ASD: Air Situation Display). However, at this level conflicts are not detected.

Every day at 06:00 am a team of MET and flight safety specialists meet and decide on traffic restrictions - if any -for the current day; landing rates may be estimated at that time for the day[2].

In the USA most airports are multi-runway[3] and landing capacity is not the dominant limiting factor like it is in Europe, where most airports have no more than 2 runways in operation at a time. Table 1 gives the specifications for parallel runways operated independently. Traffic management around the airport is of prime importance for achieving the expected maximum landing rate. The present Denver situation is summarized in Figure 1 when the sequence of arrival time is updated continuously. The margin of error is then estimated to be much less than 1 mn and is normally 10 to 20 s. From E1...E4 flight management is controlled by another system called "FAST" which operates from 20 to 30 nm prior to touch down.

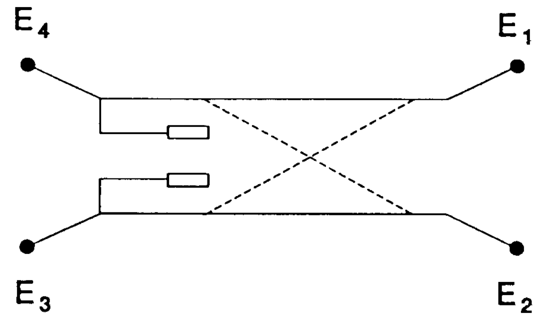


**Figure 1**

**Denver situation**

In the computer, the sequence of flight parameter modification is as follows, in order of priority :

(1) modify the "top of descent"
(2) modify the speed of the aircraft which is first in the sequence concerned
(3) modify Z by 4000 ft without modifying IAS
(4) modify Z by 4000 ft and to modify IAS
(5) modify the route.

(Surprisingly there is no discrimination in regard to the size of the aircraft, even in the re-sequencing process. This is to be corrected soon...).

R-NAV can be used before *Entry points* (or *Feeder points*) E1...E4, but not after these points up to the runways.

C-TAS manages the conflicts (this is a difference with MAESTRO or COMPAS).

**Parallel runways**

ICAO Specifications for IFR flights

| | |
|---|---|
| fully independant runways | 1525 m |
| simultaneous approaches between planes stays greater than 3.7 km | 760 m |

ECAC[(1)] proposal

| | |
|---|---|
| if airport equipped with radar refreshing data every 2.4 S | 1035 m |

*(1) ECAC : Civil Aviation Conference*

**Table 1 - Parallel runways**

[2] *The Denver area is disturbed by MET phenomena very often, mainly during summer and autumn : active storms, convexion zone, clear air turbulence, downbursts...*

[3] *Currently there are 4 runways at Denver, but two new runways are to be built soon. There will shortly be 10 runways at Houston.*

In order to optimize both the conflicts and sequencing on the entry points a criterion is used: it is a mixture of "delays", "fuel", "exchange of aircraft inside a sequence", "delay in relation to the original time of arrival". Some of these components operate also as quadratic components. This is the "Cost Index" which is derived from and embodies the "airline's rules"; some details are given in paragraph 2.3

They show that an accuracy of 30 s may be achieved for the whole traffic at the "feeder points" which allows a good initialisation for FAST.

CTAS has 200,000 lines of code.

### 1.1 Other studies connected with ATM :

A study called AFMS (for "ATM compatible FMS") is being conducted at MIT, in Prof. Bob Simpson's department. It concerns mainly the use of an automatic link either through monopulse radars with MODE S, or by satellite. As we have said previously, it is urgent to investigate how these systems can be efficiently used in addition to the digital VHF which is already in use between aircraft and airline offices. Each system has specificities as to its availability at a given time, its capacity as to the length of data transmitted and the transmission rate and the time lag between question and answer.

Another study, which has some similarity with what is suggested in chapter 8 concerns Air Traffic Management in stretches of oceanic airspace; at the present time we can consider that there are only 2 "sectors" over the North Atlantic ocean (Canada and Great Britain). Indeed, the traffic is well structured (no crossing traffic on the major part of routes, traffic spread over 7 identified routes[4]). A direct transposition to North West Europe is not straightforward. Nevertheless, the route- configured airspace over the Atlantic ocean, with only two controls, induces very penalizing constraints as to aircraft separation : if two aircraft are cruising on the same route, the first one at M = 0.76, the second one at M = 0.83 the initial separation should be 1 hour. This will soon not be acceptable and a "dynamic routing" which may allow overtaking or route exchange on a permanent or temporary basis, should be envisaged and carefully studied, taking into account wind profiles (forecast and present) and any MET constraints. It is a step toward "global optimization".

Global optimization is also being studied at Lincoln Lab (attached to MIT). An attempt to reduce US airspace to 3 areas is being studied (East : the Boston, NY, Philadelphia, Baltimore, and Washington corridor possibly including Atlanta; West : from Seattle to San Diego, and Central which, in fact will cover 75% of the USA territory). The East and West areas correspond to a "linear" management while the Central area is a distributed area. The study assumed that CNS (Communication Navigation and Surveillance) to be operational.

## 2. EXISTING AND FUTURE TECHNOLOGIES

No major improvements are expected in conventional navigational aids such as VOR, VOR-DME, ADF, OMEGA and ILS which are currently intensive use all over the world.

**The MLS (Microwave Landing System)** developed some 30 years ago will probably not replace ILS. Its main advantage is to avoid the alignment of aircraft some 5 to 10 nm before the touch down; curved approaches are possible, the final alignment being reduced to 1 or 2 nm, thus enabling aircraft sequencing and reduction in the duration of the approach phase. This is like an automatic radar controlled approach. It is, however, an expensive system which needs new on-board equipment and very expensive equipment on the ground. Table 2 shows the performance of two types of MLS equipment.

Today MLS appears to be in competition with integrated systems combining ILS (CAT III) - GPS (standard or differential) and INS. It seems increasingly unlikely that MLS will ever be implemented.

**GPS** is expected to become fully operational this year (1993). The satellite constellation will be complete (21 satellites + 3 spares). Overall precision worldwide is better than approx. 100 m in the X and Y coordinates and better than 150 m in the Z coordinates (with the exception of a few limited areas). In the northern hemisphere, which normally receives more than 4 satellites, precision will be upgraded and after a while (a few seconds) a few tens of meters will generally be accepted when an aircraft is flying straight. However the *integrety* of the GPS is not yet achieved.

[4] *These routes are re-specified every day in accordance with the MET forecast.*

| Components | MLS 800 | MLS 840 |
|---|---|---|
| Azimut | | |
| Main beam width | 3° (at - 3 dB) | 1.15° (at - 3 dB) |
| Sweeping angle | ± 10° | ± 40° |
| Number of phase shifters | 26 | 96 |
| Distance between shifters | 47.4 mm | 34.5 mm |
| Side lobes level | - 20 dB | - 24 dB |
| Pointing accuracy | ± 0.05 d° | ± 0.02 d° |
| Antenne dimension | 2 x 2 $m^2$ | 4 x 2 $m^2$ |
| Electronic systems | unique | redundant |
| Monitor | unique | redundant |
| Elevation | | |
| Main beam width | 1.67° (at - 3 dB) | 1.15° (at - 3 dB) |
| Sweeping angle | 0.9 to 13° | 0.9 to 15° |
| Number of phase shifters | 24 | 36 |
| Number of dipoles | 48 | 72 |
| Pointing accuracy | ± 0.03 d° | ± 0.02 d° |
| Height of antenna | 3.5 m | 4.5 m |
| Electronic systems | unique | redundant |
| Monitor | unique | redundant |
| MLS 800 for short runways<br>MLS 840 for large airports<br>Manufacturer Thomson-CSF | | |

**Table 2 : MLS performances**

**Differential GPS** involves new fields of application through the cooperative use of two receivers located in close proximity to each other, (up to 50 to 60 km apart), one being considered as a reference point (3-D), viz. :

- as an aid to landing, one of the receivers being at the runway threshold. CAT II landing has been demonstrated. The feasibility of CAT III by means of hybridization with INS is under study, in spite of some basic difficulties (*integrity* of the GPS signals).

- in the case of the navigation of a group of aircraft, one receiver being considered as the reference receiver, the other aircraft navigating in relation to the one fitted with the reference receiver. The relative navigational accuracy of an aircraft in respect of a reference aircraft is better than 10 m.

This last application does not seem to be well understood. We believe that differential GPS may help to solve long-range high density traffic, such as traffic over the North Atlantic.

**Monopulse radars with MODE S capability** will gradually be installed in Western Europe (full coverage has been forecast for 1998) and the USA (full coverage completed at about the same time). They will replace conventional SSRs (Secondary Surveillance Radar), thus providing additional facilities. SSR requires aircraft to be equipped with *transponders*.

The present secondary radar system incorporates MODE A (Aircraft Identification in the response 4 octal figures), MODE B (military use only) and MODE C (altitude for an altimeter set at 1013.25 hPa). MODE C implies MODE A; this means that when using MODE C the ground radar receives the aircraft identification and its altitude).

Monopulse radar has two very close beams to locate aircraft with high accuracy (order of 1° in azimuth). These radars are capable of MODE S (S for "*Selective*"). In congested areas, more than one aircraft are very often located within the beam, or two aircraft are so close that the transponder responses overlap and cannot be decoded. This is the saturating effect or "*garbling*" which affects radar performance and hence

safety. With MODE S, the ground controller may request responses on demand. Each aircraft within the detection range of the radar will not necessarily respond to the incoming radar pulse. It will respond only if its address (identity) is contained in the message which is superimposed on the radar pulse. The controller selects the aircraft to be addressed; he determines a *roll call* which can be modified at any time. Of course he still has the possibility of calling all the aircraft within its detection range, even if only for the purposes of restarting the system after a failure or a period of maintenance.

In addition to selective calls, data messages can be sent to aircraft. Only the aircraft with the identity indicated at the beginning of the message can decode its content. The address is a 24-bit message which corresponds to approximately 16 million aircraft identifications: an aircraft may be assigned an address when it joins the airline fleet and will keep it definitively.

The same facility is available for the reply. The signal sent back by the transponder may be encoded (in addition to the identification and altitude of the plane) with data concerning either the status of the aircraft or messages sent by the crew in reply to messages received.

However, data link only operates when the aircraft is within the antenna beam. Delays, which can vary between 2,5 s (two back-to-back antennas rotating at 12 revolutions per min.) to 12 s (one antenna rotating at 5 revolutions per min.). Such delays should be taken into consideration when assessing the quality of aircraft guidance.

Messages are 56 bits long. Up to 4 messages can be matched in a "long message" which provides 224 bits of data. Experiments have recently been conducted successfully.

In October 1991, a joint UK-CAA and EUROCONTROL project demonstrated a "world-first" use of the MODE S data line in a realistic ATS environment, using the BAC 1-11 research aircraft of DRA-BEDFORD, UK [Ref. 1].

Two scenarios were flown. In the first, the R/T (Radio Telephone) channel was used for all communications between the air traffic controller and the pilot. In addition to this standard communication protocol, the aircraft could also be automatically interrogated from the ground via the MODE S data link through the ARINC 429 data bus in the aircraft. In this way the ATC system on the ground could constantly check the status of the flight director, auto pilot and auto throttle instructions against the clearances given by the controller. Moreover, it was observed that merely by displaying the basic down- linked aircraft data to the controller, e.g. air speed, aircraft heading, etc., a considerable reduction was achieved in the use of R/T because questions such as: "what is your heading?" were no longer necessary.

In the second scenario, the controller sent all ATC clearances to the aircraft via the data link. They were displayed on an experimental screen in the cockpit and subsequently acknowledged by the pilot pushing a button. This acknowledgment was sent down to the ground system via the data link and the controller was advised accordingly. There was no connection, however, between the data link and the flight control instruments in the aircraft. The R/T channel was constantly available for specific pilot requests and emergencies, and did, in fact, have to be used during one of the demonstration flights. From an ATS point of view this scenario was less realistic than the first one, as the data link communication took far more time than was acceptable for time-critical clearances such as altitude and/or heading changes. Nevertheless it clearly demonstrated the capabilities of the data link as well as some of its current limitations.

Surprisingly, a method for using these resources (ground-to-air and air-to-ground messages) has not yet been finalized and studies are still in progress.

In the case of air-to-ground messages, the data comprise aircraft identification, flight path number, altitude (referenced at 1013.25 hPa), total temperature and indicated airspeed. Additional data could be added to these basic data, namely aircraft attitude, fuel reserve and on-board position. We believe that a rate of turn or roll angle or a binary indication with regard to a fixed threshold - a 5° threshold for example - would help the prediction of trajectory for the synthetic track in the processor associated with the radar.

**T-CAS :**

T-CAS (threat collision avoidance system or traffic alert and collision avoidance system) is a system which has just come into operation (in the USA). After one year of operation the results are not as good as expected. We will not discuss the reasons for this disappointment here, as they are mainly due to false alarms. An FAA report mentions that 30 approaches have been unduly interrupted in less than one year and that unnecessary changes in flight level are much too frequent. Nevertheless, the decision of 31 December 1992 to equip aircraft carrying more than 30 passengers with T-CAS II is still valid.

We would point out that T-CAS is related to airborne transponders. An aircraft equipped with T-CAS sends pulses to which all aircraft equipped with transponders

answer if they are in the T-CAS range of operation. This is an additional cause of transponder saturation, namely around an airport located in a congested area where an aircraft is seen by at least 2 and sometimes 4 radars. The operational use of MODE S with dedicated interrogations is the only way to avoid saturation.

Only T-CAS II is operational at the present time. Avoidance manoeuvres are performed only in the vertical plane (climbing, descending or modifying the actual rate of climb or descent).

In future when the number of aircraft doubles or triples, a new policy for applications of T-CAS will be needed. T-CAS III or IV, with lateral escape manoeuvres, is under study. Experiments are in process.

Systems called G-CAS (ground collision avoidance system) are under development namely at Dassault Electronique. Thanks to the extensive knowledge of terrain provided by navigation for military planes, the basic component of G-CAS is a numerical map of the airport environment (some 25 to 50 nm around).

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# CHAPTER 5

ARRIVALS MANAGEMENT SYSTEMS

# TIME BASED AIR TRAFFIC CONTROL IN AN EXTENDED TERMINAL AREA

## - A survey of such systems -

by

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- the U.S. MITRE Corporation.

## I. INTRODUCTION

### Terminal Air Traffic Management

Even though the story of data processing began at an early stage in aviation, its use by air traffic controllers is generally still limited to flight plan and radar data processing, to give them a better overview of the current traffic they have to handle. The following are examples of such facilities currently in use:

French Coordonnateur Automatique du Trafic Aérien *CAUTRA*,
German Display of Extracted Radar Data *DERD*,
British Flight Data Processing System *FDPS*,
Dutch Signaal Automated Radar Processing *SARP*,
EUROCONTROL Maastricht Automatic DAta Processing *MADAP*,
US En Route Automated Radar Tracking System/ *EARTS*,
Automated Radar Terminal System *ARTS*,

With regard more specific on-line help (advisories) to solve the traffic flow harmonisation/optimisation problem, there are currently only a few such automation tools in operation, mainly concerning Terminal Air Traffic Management *(TATM)*. TATM is understood to mean the application of a set of ground-based techniques by Area Control Centre (ACC), Approach (APP) and Tower (TWR) controllers to optimise traffic flow in and around the Terminal Manoeuvring Area (TMA).

The EUROCONTROL Engineering Directorate has been working on the concept of ground-based air traffic management automation tools designed to help achieve such traffic flow optimisation since 1978. Because a number of research projects had been initiated in different places around the world to meet the difficulties associated with the growth in air traffic, the author of this report was requested to undertake a study on the current feasibility and to make a qualitative comparison of the different approaches to the problem.

Research teams in several organisations/administrations directly involved in terminal automation were therefore contacted, as follows:

- The EUROCONTROL Engineering Directorate, regarding its Zone Of Convergence *(ZOC)* project.

This Chapter is based on the report "Time based Air Traffic Control in an Extended Terminal Area" (EUROCONTROL Doc. 912009) by Eric Petre

- the German DLR, regarding its Computer Oriented Metering Planning and Advisory System *(COMPAS)*.

- the French CENA, regarding its Means to Aid Expedition and Sequencing of Traffic with Research of Optimization *(MAESTRO)* system.

- the British RSRE, regarding the work done by its Terminal Control Systems Development Group *(TCSDG)* and recent Predictive Approach Control Tactical Advisory System *(PACTAS)*.

- the Dutch RLD, regarding its for their Automatic Slot Assignment *(ASA)* system.

- The Federal Aviation Administration, regarding the numerous projects it has sponsored with different companies, and consolidated into the Terminal Advanced Automation System *(TAAS)*.

- The NASA Ames Research Center, regarding the Center/Tracon Automation System *(CTAS)*.

- The NASA Langley Research Center, regarding Traffic Intelligence for the Management of Efficient Runway-scheduling *(TIMER)*.

- Massachussets Institute of Technology, regarding the various studies undertaken at the Flight Transportation Laboratory.

- The Lincoln Laboratory, regarding the Terminal Air Traffic Control Automation *(TATCA)* project.

- The MITRE Corporation, regarding the studies by its Air Transportation Engineering Division.

Only three of these systems are currently in operation, viz:

- the Dutch ASA system, which serves both Schiphol approach and area control; this runs under the SARP system and was commissioned in 1981;

- the German COMPAS system, using the DERD - UKD environment, which has been used by the air traffic controllers at Frankfurt since October 1989;

- the French MAESTRO system, which has been operated with CAUTRA 4 at Orly airport and Paris ACC since December 1989.

The following chapters will briefly describe the various solutions proposed by the organisations contacted (publication references for each system are given at the end of this report), and will endeavour to identify the comparative benefits or limitations in each case. Nevertheless a distinction must be drawn between operational tools and research projects, where the different inputs/outputs to the system presented will to be taken more as examples of what is possible, or as results showing the importance of given variables which could be omitted in an operational environment. It should also be borne in mind that this report was made on the basis of the information and publications available on the different systems, and could therefore only reflect the situation for the time at which the information was valid (August 1990). This will be particulary true in the case of research work, which advances almost daily.

## DEMAND ON THE SYSTEM

### Air travel forecast

The development of the air transport industry is one of the major achievements of modern times, contributing significantly to economic growth, in both the business and leisure fields. The average annual growth in the number of passengers has been about 6% in Europe, but a significant jump has occurred in the past two to three years, with passenger growth topping 10% per year. A report by consultants SRI International forecasts that the number of passengers will nearly double by the year 2000 and triple by 2010. With increases in aircraft size and load factors, the number of aircraft movements will increase somewhat more slowly, but even allowing for this and alternatives such as high-speed rail travel, it is set to more than double by the year 2010.

### Airport capacity

The SRI report also makes an evaluation of airport capacity potential and constraints, focusing on 27 airports representing the major traffic centres in Europe. Each airport was evaluated in terms of its ability to accommodate future growth on the basis of present airport plans and/or SRI-identified potential runway enhancements. The conclusion reached was that unless they are upgraded, the majority of these 27 key airports will be unable to accommodate air traffic demand.

Terminal areas are the ultimate constraint on the capacity of the airspace system, a bottleneck in any route structure where flights converging from a number of directions must be funnelled onto one or two active runways. When terminal capacity fails to keep pace with increasing traffic demand, delays occur both in en-route airspace and at airports prior to take-off.

### Airspace capacity

The structural components of airspace (route segments, airway intersections and airspace volumes over and through which aircraft move) definition also give rise to capacity problems. Again the SRI report finds that the entire route and sector structure over large areas of Western Europe will have to be restructured in order to handle projected traffic. Such a rerouting/resectorisation process would need to encompass military airspace. Route development may even require some modification of TMA interfaces and national boundary-imposed constraints on routes and sectors.

It would seem, then, that the airport and airway congestion problems already facing us will pose a serious threat to future expansion, and the handling of overall aircraft movements

will need to be efficiently tailored to the new environment if the security, cost and comfort of air transport are to be maintained at an acceptable level.

As we shall see, the various works undertaken in connection with terminal air traffic management automation prove that opportunities exist for increasing the throughput of existing terminal areas by the provision to terminal control of automation tools designed to increase control efficiency (i.e. reduce delays, increase fuel-efficient operations, improve traffic flow and at the same time reduce controller workload, improve the co-ordination of controlled areas and maintain safety levels).

**Defining the problem**

If these goals are to be achieved, the problems of the terminal area need to be closely analyzed.

Components :

- an airport layout : number of runways available, possibility of using one or more runways for take-off, simultaneous landing and take-off, taxiing, access to gates, etc;
- a terminal area airspace structure, arrangements of TMA, Control Terminal Region (CTRs), airways, etc;
- a radar coverage system : primary, secondary, ground movements, etc;
- the different procedures used to fly into the area, e.g. Standard Instrument Departure and Arrival Procedure (SIDs and STARs), preferred company operating procedures, etc.

Available data :

- Flight plan (recording & activation);
- radar data (accuracy of data, combination of primary & secondary);
- atmospheric conditions (accuracy, update).

Models used :

- aircraft behaviour and performance model;
- wind and temperature distribution across the area;
- flight profile generation techniques.

Any data processing system using these elements can be used to provide a picture of the current traffic situation. This knowledge of the actual state of the traffic, coupled with the models of behaviour available for the different components of the problem, allows broad predictions of the future situation to be made. Future traffic flow can be projected, in order to highlight potential traffic trouble. After examination of the different combinations and permutations of control action, measures can be taken to enhance the current traffic situation. This is in fact the mental process followed by the air traffic controller when handling the traffic. The only difference from having a data processing system helping him in such a process is that the controller can base his prediction only on his experience, a sort of unconscious statistical model of the whole environment, whereas we can provide much more complex models, able to take into account a much larger number of variables.

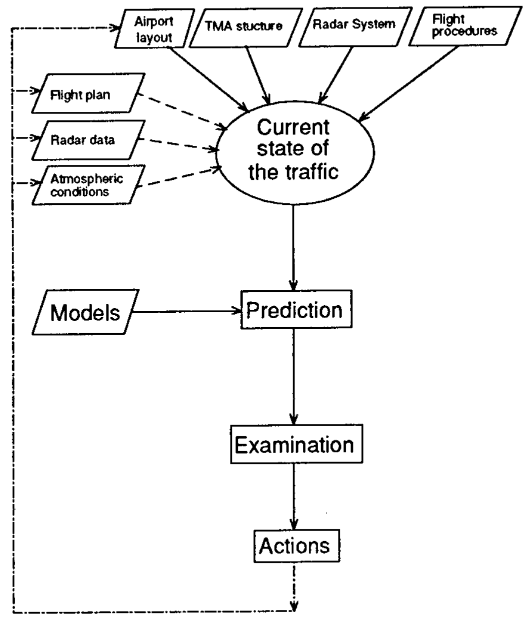


**Figure 1 : The TMA problem**

This clearly shows where we have an advantage over current ATC traffic handling procedures : we can expect new equipment to go much further in terms of traffic complexity and timescale, to a degree impossible to achieve simply by increasing the number of controllers for instance. This is by no means to say that future systems will replace the controller, but they will serve to help him when he reaches his human limits.

We have seen that the difference between a human process and an automated one lies chiefly in the models used. "Examination", for example can be divided for automated process purposes into scheduling, sequencing, profile planning. These tasks can also be performed in different ways, as we will see, and the impact of the "actions" (mainly advisories) resulting likewise varies. This will be covered for each system in the next chapters.

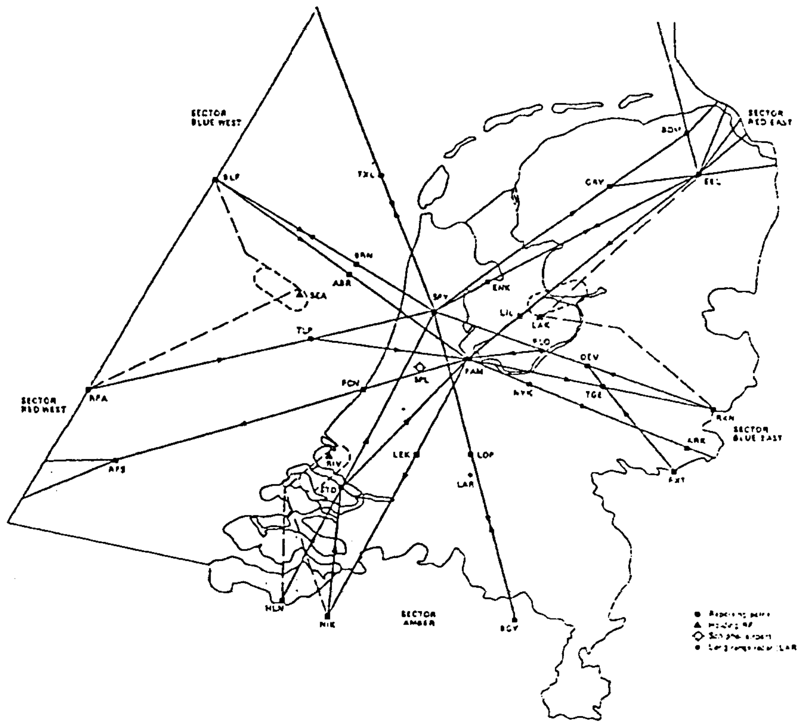


Figure 2 : The Netherlands airspace structure

## II. AUTOMATIC SLOT ASSIGNMENT

The Netherlands airspace structure is depicted in Figure 2. This star route structure is characterised by twelve different entry points, the routes converging on two VOR's (SPY and PAM), and eventually going through one of the three holding areas (LAK, SEA, RIV).
Hand-off from one sector to another takes place somewhere in the complicated crossing area over the SPY and PAM VOR's, depending on the traffic situation. The Netherlands Department of Civil Aviation (Rijksluchtvaartdienst or RLD) very early saw the need for accurate Estimated Times of Arrival (ETAs) for SPY and PAM, in order to maintain an efficient flow and conflict-free planning of the traffic in this area. This planning is carried out by a special planning controller for the SPY-PAM crossing area, who also co-ordinates between the sector controllers. He has no executive task and is helped in this planning task (e.g. conflict search) by the computer and display system (Signaal Automatic Radar data Processing - SARP) at present in use. This system, serving ACC, APP and TWR control, employs automated radar data processing and flight plan processing. The SARP "trajectories prediction" function is also used to provide ETAs for Schiphol, permitting automatic planning of traffic inbound to Schiphol airport.

SARP processes divers groups of data, viz:

- flight plan data, containing information such as aircraft type, planned route, ETA at the entry route point, requested flight level and associated cruising speed;
- the SARP database, which contains pre-stored aircraft performance data as well as route geometry information. The aircraft performance information is available for 34 performance categories, each representing one or more aircraft. The route geometry information contains route points, co-ordinates and strings of subsequent co-ordinates for procedures such as STARs and SIDs;
- the meteorological database, providing upper airspace wind and temperature data, updated every 6 hours;
- the radar data from both long-range radar and terminal area radar.

These data allow SARP to process its Flight Category concept, which functionally defines some 60 specific flight types such as transit, outbound Schiphol, inbound Schiphol flights and so on. For each flight type a single trajectory prediction scenario is valid.

The early years of SARP saw the implementation of calculation rules based on parametric studies. The concrete results were very disappointing, so it was decided to go to a calculation system based on actual ground speed and obeying parametric laws on basis of flight levels. The different coefficients are provided by the SARP database, which draws on models validated by statistical studies based on previous flight-plan data. The equations so produced are used to predict flight-profiles, which are continuously corrected by reference to radar information (on-line operation) and logged into the system for future system tuning (aircraft models update).

The predicted times (ETAs) over specific points (beacons, reporting points, etc) produced are used in different ways in the system. They can be considered as data items for the controller and printed on paper strips or shown in the strips on Electronic Data Displays (EDDs). They are also used to trigger system activities such as data distribution, automatic conflict search and planning. A very important aspect is their use as inputs for these various automated functions.

Amongst these functions, the are which most concerns us here is the automatic planning of inbound traffic for Schiphol airport. The Approach Planning Controller can decide, in the light of the circumstances, either to make use of an automatic planning routine for all IFR traffic which will land on the main landing runway, or to do it manually. This planning follows the First-Come-First-Served-At-the-Runway principle based on an ETA for Schiphol, and makes use of the current runway capacity. This capacity depends mainly on the weather conditions and is manually fed into the system in the form of a landing interval (LIV). A further important element for planning is the latest assigned planned landing time (LAS) or slot time for the runway.

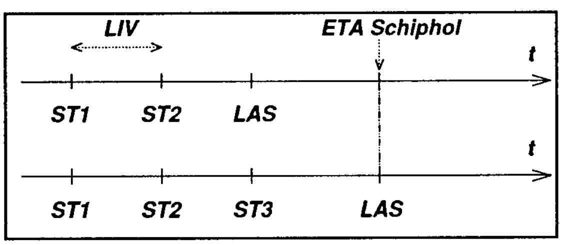


**Figure 3 : Sequencing without delay**

Just before the planning of an inbound flight starts, a new trajectory prediction is carried out in order to obtain new ETA values. At the planning moment (which is 7 minutes prior to ETA on a stack, to be considered as a point and not necessarily as a holding pattern), the ETA for Schiphol is compared with the latest assigned slot time for the runway. If the ETA Schiphol is greater than LAS + LIV, there is no delay and a slot time equal to the ETA for Schiphol will be allocated to the flight. The LAS for the runway will also be equal to ETA Schiphol.

If the ETA Schiphol is smaller than LAS + LIV, the aircraft has to be delayed. The first available slot for the aircraft is LAS + LIV, and that time slot will be allocated. The delay

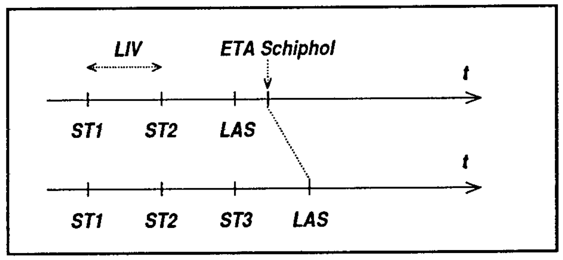


**Figure 4 : Sequencing with delay**

will be presented on the tabular displays of the controllers in the form of an Expected Approach Time (EAT). This EAT indicates when the aircraft is allowed to leave the holding RP and enter the TMA; the final result of the inbound planning provided to the controllers is thus the Entry Sequence List (ESL), displayed on the radar screen.

The controllers have access to several functions affecting system reactions and operation, such as indefinite delay in holding, technical delay in holding, indefinite delay en-route, holding within the Schiphol TMA, change of main landing runway, missed approach, diversion to an alternative airport, display status VFR flight, etc. It has also simple "manual override" functions for operational flexibility. For instance, when traffic demand is high, the controller can manually resequence flights, for example to minimise the effect of large separations due to wake vortices; similarly when a traffic peak is expected, delays can be minimised by acceleration of the first aircraft of the peak by means of tactical control. The planning mechanism adjusts itself automatically to this situation by planning two aircraft at the same landing slot. It is up to the executive controller whether to accelerate the first or delay the second aircraft to guarantee separation in this case.

A further function entrusted is that of automated departure planning. Indeed, the proper planning of outbound aircraft is a procedure requiring co-ordination activities between ATC units and, under certain conditions, adjacent flow-control centres, before the actual clearance is given to the pilot. This function supports co-ordination activities and also makes use of trajectory prediction results. In fact, upon first contact between the pilot and the local TWR for startup authorization, a Revised Estimated Time of Departure (RETD) is manually calculated by the TWR controller, taking into account the pushback procedure and the taxi time to the take-off runway. This RETD is inserted at the TWR itself into the system, which carries out the trajectory prediction using the standard instrument departure information plus the route/level data as filed in the flight plan. For boundary points an automatic conflict search is conducted to compare the new flight with all other flights which are to pass these points. In this conflict search a number of criteria are defined for each RP (FL, aircraft on the same track or crossing, etc) which in turn are used to check whether the aircraft can pass the specified RP conflict-free. The ETA for the boundary exit RP, together with conflict search

information, is presented to the sector en-route controller. He may inform the system by means of a simple input (RETD-acknowledge) that the aircraft is cleared to pass the sector under the proposed conditions. He can also modify the RETD and/or the FL condition(s) by means of an input into the system. The acknowledgement or the new RETD is then shown to the start-up controller in the tower.

The current system is a centralised one, based on a double host system (Master-Cluster interdependency). The various workstations providing TWR, APP and ACC functions thus serve as terminals of that host system. Work is now underway on the development of a new system, called the Amsterdam Advanced ATC System (AAA), which will replace the present SARP in the course of 1992. The main reasons for the system upgrade are the age of the existing one (nearly 20 years) and the lack of system modification potential and independence by virtue of the purely centralised data processing concept. The aim is now to move over to a decentralised system, with powerful workstations connected to servers via a high-speed LAN. Basically, all the functions will remain the same as before, although there will, of course, be some new enhancements. It will certainly not lose the current advantages, such as the use by TWR, APP and ACC of the same centralised data. As far as the automatic slot assignment procedure is concerned, the system will be extended to a double landing runways system served by preferred stack routes.

## III. THE COMPAS SYSTEM

The operational area covered by the COMPAS system is depicted in Figure 5. It covers an area of about 100 NM around Frankfurt up to FL 250. The diagram shows a schematic picture of ten different approach routes and three main approach navigation fixes : GEDERN (B1), SPESSART (B2) and RUDESHEIM (B3).

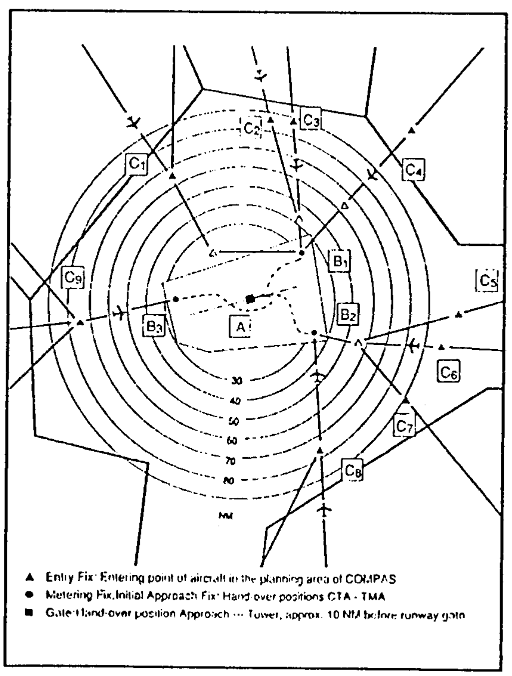


**Figure 5 : Frankfurt airspace structure**

The aim of the Computer Oriented Metering Planning and Advisory System is to assist the air traffic controllers using a traffic flow computer in their planning and control of approach traffic. Its principal task is the creation of a proposal for:

- integration of individual flights into the overall inbound flow,
- the planning of the sequence of these flights,
- information regarding the implementation of this plan.

It base its processing on three different types of data, viz:

1. Basic data and models which are static during the planning process : aircraft performance data, airspace structure, approach procedures, separation values, wind model;
2. Event-oriented data, which change with "low frequency" : entry or departure of an aircraft into or out of the system, flight plan data, wind data;
3. Dynamic data, which change with "high frequency" current flight conditions (position, speed, height, deceleration rate, descent rate).

Table 1 gives an overview of all operational data needed and handled via interface with the main ATC computer:

- radar data interface, based on the DERD/MC system of the BFS,
- flight plan and weather data interface, based on the ZKSD and the DUEV system.

Both prediction and planning processes are initiated on the entry of an aircraft into the controlled zone. After identification, a correlation is made between the radar data and the flight plan data, and entry speed is computed from radar data. COMPAS uses a simplified procedure for flight path prediction. It works with little basic data, takes into account the varying aircraft performance categories, and is oriented as far as possible to realistic boundary conditions. The following considerations are assumed :

- Descent and deceleration phases are carried out with idle thrust setting.
- Clean flaps/slats configuration.
- Constant descent speed.
- Minimum cost speed recommended by Lufthansa.
- average flight weight (empty weight + 70% additional load).
- knowledge of the future route followed by the aircraft (ground track and altitude distribution along this track).

With quadratic polynomial laws (9 coefficients) for each aircraft type modelling its performance, COMPAS can determine the descent or deceleration rate and so predict estimated arrival time at the metering fix (hand-over position ACC-APP; see Figure 5) and at the gate (10nm before runway).

| Target Information | Source |
|---|---|
| Target coordinates relative to the destination | DERD-MC |
| Callsign | DERD-MC |
| Assigned code number | DERD-MC |
| Radar antenna for this target information | DERD-MC |
| Mosaic information | DERD-MC |
| **Flight Plan Information** | |
| Callsign | ZKSD |
| Destination airport | ZKSD |
| Type of aircraft | ZKSD |
| Weight class | ZKSD |
| Entry Fix into the TMA | ZKSD |
| Metering Fix | ZKSD |
| Estimated time over Metering Fix | ZKSD |
| Estimated cruise speed | ZKSD |
| **Weather Information** | |
| Height/Wind profiles | ZKSD |

**Table 1 : Operating data required by COMPAS**

In addition to this Estimated Time Over Gate (*ETOGT*), the earliest possible arrival time (*EETOGT*) which the aircraft can achieve under current conditions without thrust increases is calculated.The comparison of these two values shows the potential of temporal acceleration which can be used for arrival flow smoothing.

| Prec. \ Succ. | Heavy | Medium | Light |
|---|---|---|---|
| Heavy | 107 s | 133 s | 160 s |
| Medium | 80 s | 80 s | 107 s |
| Light | 80 s | 80 s | 80 s |

**Table 2 : Time separation matrix**

This set of EETOGTs is used to build the sequence according to the principle of First-Come-First-Served. A search is made to establish whether the minimal permitted time separation between aircraft at the gate is being met. For this purpose, a separation matrix is used (see Table 2), which contains the minimal permitted time separation between a combination of preceding and succeeding aircraft according to their weight class. If at least one time conflict is detected, then a "conflict resolution" function is carried out. To determine which aircraft to delay or to expedite in order to obtain a conflict-free stream, it uses a branch and bound algorithm with a cost function (total delay time) for delay assessment (i.e. the proposed sequence guarantees that at the gate, every aircraft is separated in time by the required value, and that the sum value of every individual delay reaches its minimal level).

The output of the result of these sequencing and scheduling functions is displayed to the controller concerned on a colour screen (Figure 6). The various aircraft in the arrival flow are

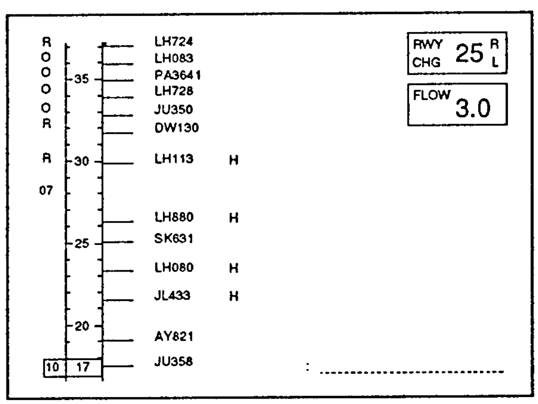


**Figure 6 : COMPAS Display**

listed sequentially on a time scale for the next 20 minutes, with the earliest arrival at the bottom. All planned aircraft are displayed with their callsign and weight class (H for Heavy, L for Light).

The following colours are used, to display to the controller the direction from which the arrivals are coming :

*Yellow* : traffic from the South (B2)
*Red* : traffic from the West (B3)
*White* : traffic from the North (B1)

The bottom box indicates the actual time on the left side of the time scale, and the number of minutes by reference to the Gate (APP position) or the Metering Fix (ACC position).

The letters to the left of the axis are the advisories provided by COMPAS to establish the planned arrival stream:

X eXpedite : an acceleration up to 2 min.
O On schedule : no delay / no acceleration.
R Reduce : up to 4 minutes delay.
H Holding : more than 4 minutes delay.

The controller can move a cursor up or down the time scale to identify a specific aircraft for modification purposes. At the top right, we find the landing direction in use and the airport acceptance rate (flow). Flow 3.0 means unrestricted traffic flow with 3nm minimum separation when permitted.

Interactions with the COMPAS computer are possible via the input keyboard, allowing 2 types of function:

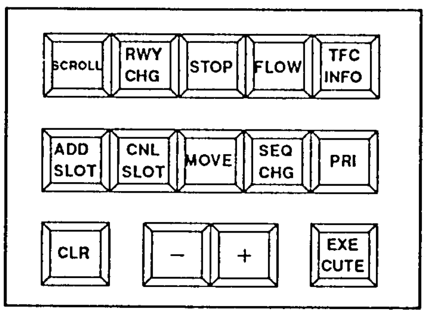


**Figure 7 : COMPAS keyboard**

- planning modifications;
- changes in basic data.

Inputs concerning alteration of the basic data can be performed only by the APP controller. Only his keyboard has the function keys required for this purpose :

**FLOW:** Alteration of separation interval
**RWY CHG:** Change of landing direction
**STOP:** "H" indicator at all positions, e.g. in the event of disabled runway.

Inputs for plan modification can be entered at all positions :

**ADD SLOT:** Addition of an approaching flight with no flight plan available

**CNL SLOT:** Cancellation of an approaching flight
**MOVE:** Moving the planned time of an approaching flight
**SEQ CHG:** Changing the sequence of two successive flights
**PRI:** Assigning priority to an approaching flight
**TFC INFO:** Display of identities of approaching flights from other sectors

In addition there are general purpose function keys :

**CLR:** Clear input process
**-:** decrease parameter value or moves cursor position on the time scale
**+:** increase parameter value or moves cursor position on the time scale
**EXECUTE:** Execute input process
**SCOLL:** Scrolling of displayed section of the time ladder

COMPAS is functionally subdivided into three parts, each one running on a separate computer :

- Front-End Computer : Interface to the ATC main computer (radar, flight plan and weather data input).
- Central Computer : Flight progress calculation/prediction. Sequencing, scheduling and derivation of proposals for flight progress control (Micro VAX II).
- Workstation Computer : Formatting, buffering and output of display data. Keyboard data input and formatting and local display changes support (Personal Computers).

These three entities are connected to the same Ethernet network.

## IV. The MAESTRO System

The operational area covered by the MAESTRO system is depicted in Figure 8. It covers an area of about 100 NM around Paris. The main entry points in the ACC sectors are MOU, ATN, DIJ, ROLEX, BARAU in the east and AMB, SABLE, FERTE, DVL in the west. For the TMA, inbound flights pass through Melun, Marli and Boursonne.
In fact, two main traffic flows, which are controlled by specific sectors (ACC east positions : TU, UT, AR and AO sectors, and ACC west positions : UK, UX, TH and TW), feed Orly Airport. These two flows (plus a secondary one for flights coming from Boursonne) are merged in order to provide a single flow for the runway used for landing. The GOT (Gestion Optimisée du Trafic - Optimised Traffic Management) function, shared by ACC and Orly Approach, is devoted to the definition of a strategy of actions on the traffic to smooth out the flow rate inbound TMA and coordination of the actions undertaken by the different sectors involved. GOT start handling the traffic at ACC entry points till the TMA boundaries (55 to 30 minutes before landing).

The main aim of MAESTRO is to provide help to that position. It bases its computation on the data available from

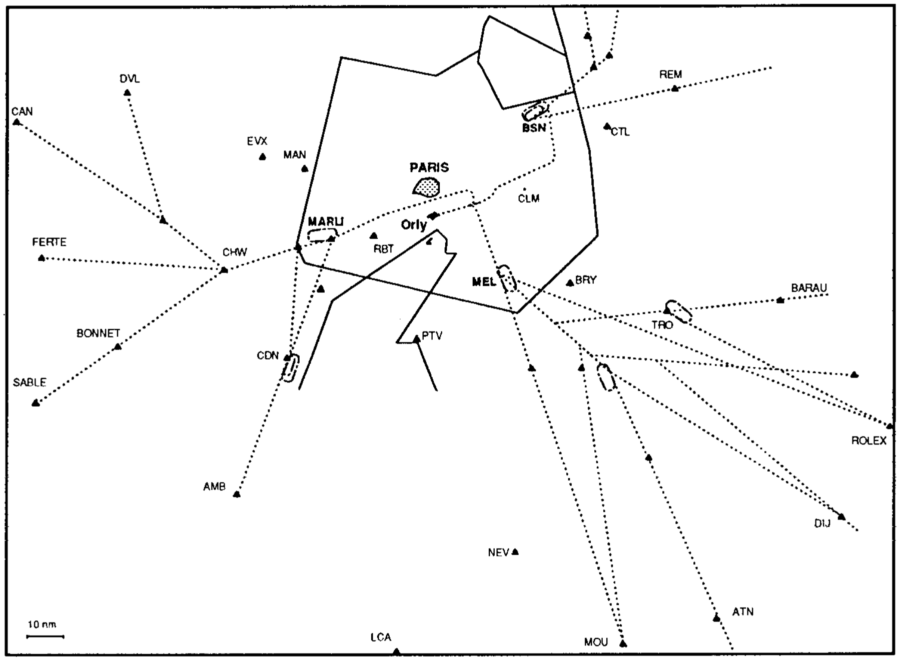


**Figure 8 : Paris-Orly airspace structure**

the STPV (CAUTRA flight plan processing module) at the entry points of the ACC, updated every five minutes by the STR (CAUTRA radar data processing module). This allows CAUTRA to provide estimated times at the TMA entry points (**HEBCs**), used by MAESTRO to calculate estimated landing times (**HETMs**). MAESTRO takes into account operational "short-cut" in the actual route followed or a flight speed lower that in the CAUTRA flight plan. Using this set of HETMs, the MAESTRO sequencer module provides ordered landing flow and sequenced arrival time at the runway (**HASM**) for every aircraft, separated in time by at least the duration of the runway landing rate. The delay (**D = HASM - HETM**) is split into a delay to be absorbed within ACC (**Dc**), within APP (**Dp**) and what is know as "pressure at the runway" (**p**).

The Dc is characterised by a maximum value, a function of the class of aircraft, the route and sectors characteristics :

| | | |
|---|---|---|
| fast | -> | MOU, ATN, DIJ, ROLEX, BARAU, AMB, SABLE, FERTE, DVL, "ELSE". |
| slow | -> | All. |

These 11 values specify the maximum time absorbable in a linear way (speed and trajectory control, without using holding stack). This is also applicable for the Dp value, for which the maximum is only a function of the entry point into the TMA and the runway configuration :

MEL, MAR, BSN -> east and west.

The pressure at the runway is an amount of time (120 sec, except for the east STAR from Melun where it is 180 sec) to be spent in the TMA, in order to allow the control team to have some flexibility in regard to the scheduled arrival time.

The rules for assessing the division of the delay (**D**) between TMA and ACC are illustrated by the following figure 9.

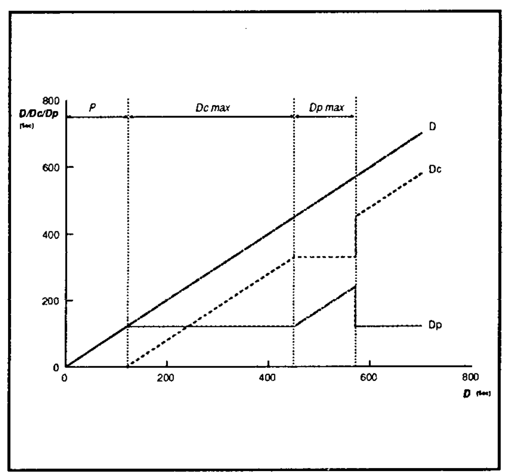


**Figure 9 : Delay assessment**

**To achieve these HASMs, MAESTRO provides the control team with the required entry time (HPS)** into the control area. This is done by subtracting from the sequenced arrival time **HASM** the delay (**D**) to be absorbed and a statistical buffer (**F**) time to cross this area. There are 12 possible values for **F**, depending on the kind of aircraft (fast, slow), the route entry (MEL, MAR, BSN) and the active landing runway configuration (east, west).

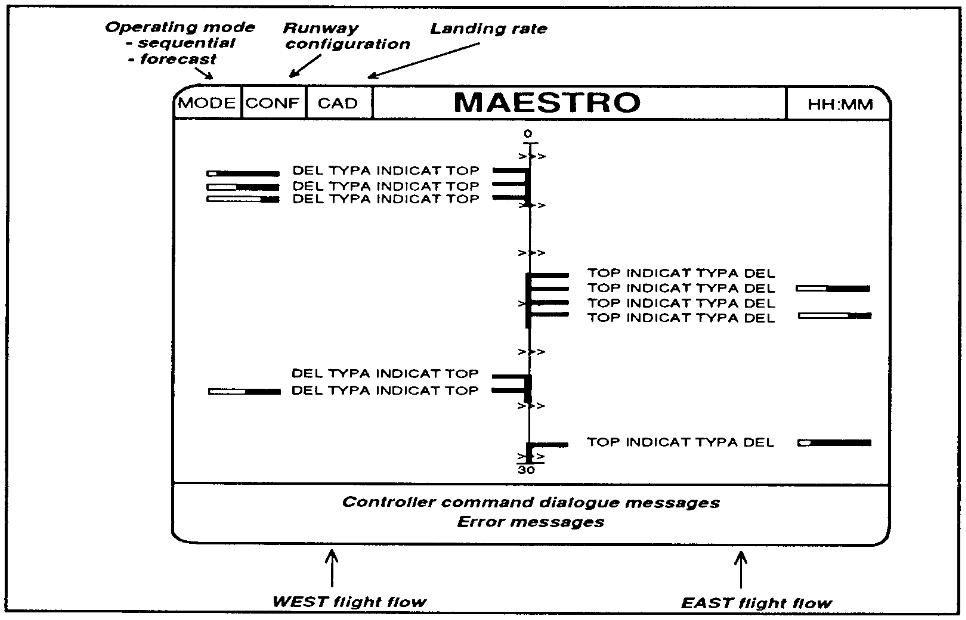


**Figure 10 : MAESTRO image**

The basic data presented on a colour screen to the controller are :

- the sequence of flights in an ascending order of landing time;
- the initial delay **DEL** to be absorbed;
- the aircraft type **TYPA**;
- the call sign **INDICAT**;
- the time **TOP** to spend before reaching the entry point (HPS).
- a delay compensation indicator, represented by a rectangle showing the ratio between the delay already absorbed and the initial delay.

Blue, yellow, violet and red are used to differentiate the control actions to be performed at the en-route centre in order to achieve the HPS proposed (speed increase or reduction, heading changes, holding stacks).

The GOT also controllers also commands to modify the flight parameters or the proposed sequence. Some of these could be approved by another position (e.g. Approach) before validation, or available only at a specific position (e.g. change of runway configuration).

There are three types of commands, available via the keyboard:

*- Commands modifying operational data :*

**CAD** : runway landing rate.
**CONF** : runway configuration.
**MODE** : MAESTRO operating mode : Sequential (active control position),

Forecast (passive monitoring).

*- Special commands :*

**ECHE** : screen time scale (0-30 min / 10-40 min / 10-55 min).
**ANN** : cancellation of a command during execution.

*- Flight commands :*

**DEPL** : movement of a flight in the sequence.
**DEPP** : movement of a flight packet.
**SUPP** : cancellation of a flight from the sequence.
**RDG** : overshoot of a flight from the sequence.
**QRE** : modification of a flight QRE.
**RCLP** : partial update.
**RCLT** : total update.

In addition to the above, all the parameters characterising the operational environment (runway landing rate, runway configuration, operational delay data, etc) are accessible with the help of dialogue menus and data entry screens.

The MAESTRO system runs on the CRNA/NORD host computer (DATA GENERAL MV7800). The application is thus operational in an AOS/VS environment, written in ADA using LIMAS (interface software supporting the X.25 exchange between STPV and MAESTRO) and ADA Graphic Library for the GKS development handling the SIGMEX graphics consoles.

The short-terms evolution of MAESTRO will mainly concern:

- **from the functional angle:**

improvement of calculated landing time accuracy,
enhancements to the sequencing algorithm used,
proposals for delay absorption actions (speed and heading

advisories),
processing of take-offs close to the landing field,
management of two active landing runways by a single MAESTRO system.

- **from the technical angle:**

improvement to graphic console supervision,
installation at other airports, such as ROISSY, LYON, etc.

## V. THE TCSDG TOOLS

The research work in the field of arrivals management carried out at RSRE, which started early in 1984, has led to the development of three experimental prototype computer-based tools for assisting air traffic controllers with the flow management of traffic arriving at busy major airports. These tools are:

1. *A Landing Order Calculator* (LOC), which automatically calculates landing order and Terminal Approach Times (**TAT** - planned time of arrival of an aircraft at a point where it enters the approach sequencing area) for aircraft which are still at their cruise levels, and plans a landing sequence accordingly;
2. *A Speed Control Adviser* (SCA), including all the functions of the LOC, and in addition calculating the descent speeds needed to achieve the planned Terminal Approach Times;
3. *A Predictive Approach Control Tactical Advisory System* (PACTAS), designed to provide the approach radar controller with a predictive service to help with the task of delivering aircraft at the arrival runway.

The aim of the research activity was to investigate how computer technology could be used to assist Air Traffic Control in dealing with the special problems of traffic arriving at major airports such as London Heathrow. The construction of these experimental prototype tools takes place within a real-time environment in which controllers can make use of the tools while controlling simulated traffic.

### Landing Order Calculator

As the tool identifies, typically 150-200 nm before the airport, a trajectory prediction module is initiated, in order to determine a **Preferred Landing Time**. This is done by predicting the time the aircraft will take to fly from the point where the calculation is being made to the runway, given the current aircraft position, height and speed, plus the normal route to the runway (including ATC altitude constraints), the normal methods of operating the particular type of aircraft, and the wind conditions. However, several aircraft might have the same (or very similar) Preferred Landing Times, so a procedure for establishing Allocated Landing Times is needed.

Instead of allocating landing times at some fixed distance out from the runway (Entry points into the controlled area), a "**Time Horizon**" method is used and reference made to an aircraft "crossing the Time Horizon" when it passes the point in its flight which is so fixed (typically 25 min) before its Preferred Landing Time. At this moment it becomes eligible for sequencing, using a First-Come-First-Served algorithm. The aim of the allocation process is to allocate Terminal Approach Times to the traffic in such a way as to achieve a known delivery rate into the approach sequencing area. This rate is determined by a notional landing rate value, and a fixed interval between successive aircraft is assumed. Two different states can therefore be specified, viz:

- a busy state, allowing aircraft to be requested to fly faster than preferred, in order to increase runway capacity when traffic intensity is high;
- a non-busy state, where the earliest landing time allocated would be the preferred landing time.

An important parameter here is the **Maximum Absorb Time**, defining the amount of delay which it is feasible to absorb within the approach sequencing area by a combination of speed reduction and path-stretching. This is a function of the geometry of the available airspace, and the chosen parameter value reflects the desired situation under normal operating conditions. Aircraft will be expected to hold if the required delay (difference between the preferred landing time and the allocated one) is greater than the Maximum Absorb Time, and in any case, if the preceding aircraft was holding and has not departed the stack some suitable margin ahead.

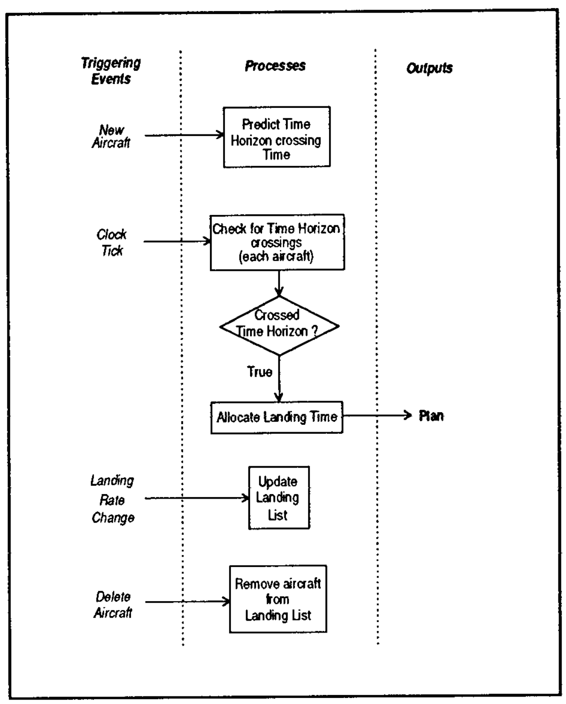


**Figure 11 : LOC Functions**

In the case of an aircraft which is not required to fly a holding pattern, therefore the TAT will be the estimated time of arrival at the terminal approach fix (up to about 30 nm out from the runway), derived from subtracting from the preferred landing time the normal time taken to traverse the approach sequencing area (assuming a defined standard routing) plus the value of the delay to be absorbed in the sequencing area. If the aircraft is required to hold (because the delay value is greater than the Maximum Absorb Time), then the TAT is the time to quit the holding pattern. This is computed as the allocated landing time minus the standard approach sequencing area traversal time.

The main outputs from the tool are referred to as plans. A plan is generated for each arriving aircraft and can be revised when the landing rate is changed. It comprises a Landing Sequence Number for the appropriate airport, a Terminal Approach Time and a Predicted Stack Arrival Time (which is the same as TAT if the aircraft is not required to hold).

There are three possible inputs to the LOC, as follows:

- The landing rate may be altered to reduce or increase the planned rate of delivery into the approach sequencing area;
- The allocated sequence numbers may be overridden by the controller swapping any two aircraft in the order;
- The Maximum Absorb Time parameter may be adjusted if prevailing wind conditions or visibility change significantly.

Landing Sequence Numbers are displayed both in track labels on the radar displays, and in "strips" on a flight progress Electronic Data Display (EDD). TATs are displayed in the latter display only. Both the TATs and the Landing Sequence Numbers are displayed as soon as allocated, i.e. when the aircraft is about 25 min from the airport. The LOC also advises the controller of the requirement to hold an aircraft by appending a single "h" character to the aircraft information displayed.

**Speed Control Adviser**

The Speed Control Adviser (SCA) includes the functions of the LOC but goes further by computing a speed for each arriving aircraft. The speed is calculated so that the aircraft meets its allocated landing time by absorbing the required delay and increasing speed if necessary. The SCA's rules for both absorbing delay and computing TATs are slightly different from those used by the Landing Order Calculator. Three different cases are now considered :

- the total delay can be taken up only by speed control between the top of descent and the Terminal Approach Fix, so the TAT will be the allocated landing time minus the standard approach sequencing area traversal time;
- the total delay exceed that which can be taken up by flying at minimum speed, but the remaining delay is smaller than the Maximum Absorb Time, so the TAT will be the ETA at TAF assuming minimum descent speed;
- same case as above, but the remaining delay is greater than the Maximum Absorb Time. This means that at least one minimum stack orbit must be flown and TAT is the allocated landing time minus the standard approach sequencing area traversal time.

As against the LOC, there are thus two additional functions and one new triggering event, viz:

**Compute Speed** : at the same time a landing time is allocated, an appropriate descent speed is chosen to meet the time.

**Update Landing List** : in response to a landing rate change request the landing times for each entry in the landing list are adjusted to reflect a new landing rate. In addition to new TATs, new speeds are computed for those aircraft which still have scope for absorbing delay en-route.

The new triggering event is generated by a request from the controller for a new plan, which sets off the computing of the appropriate CAS for descent. The two last cases are obvious (delay exceeding that which can be taken up by flying at minimum speed descent), because both involve descent at minimum descent speed. But for the first case the arrival times flying at minimum, maximum and preferred speeds appropriate to the performance of the type of aircraft are computed using trajectory prediction. This produces three couples of speeds and times of arrival enabling the target CAS to be derived by interpolation using as an approximation:

$$V+a=\frac{k}{(T+b)}$$

where speed (V) is assumed to be approximately inversely proportional to time (T) and a,b and k are constants. If the three points are in a distinct order, we have three solvable simultaneous equations determining a,b and k and telling us to know the appropriate speed for a given landing time.

In addition to the outputs of the LOC, therefore the SCA gives the speed (CAS) and predicted time for top of descent for every aircraft, with this information being displayed to the controller, who can issue the speed instruction at any point between its being displayed and the aircraft's being in a position to implement it. The working environment was the same as for the LOC, with each controller position having:

- a simulated radar picture with the ability to display aircraft labels which could include Landing Sequence Numbers;
- a tabular display to show sequence numbers, TATs and planned speeds for each aircraft,
- a means for updating the flight progress data, and
- a means for interacting with the planning process.

This was achieved by using three displays on each sector position. A plan view radar display (PVD) was mounted vertically in front of the controller, with a vertical electronic

data display (**EDD**) of flight progress data adjacent to it. A data entry device referred to as the Flight Progress Updating Device (**FPUD** - colour monitor with touch-sensitive overlay) was mounted below the PVD.

Both LOC and SCA were tested in an experimental environment using a Traffic Sample Generator, a Skeleton Control Centre Software, an Air Traffic Simulator and an Automatic Controller real-time multi-tasking program.

**Predictive Approach Control Tactical Advisory System**

When used in conjunction with an arrivals management system able to identify a suitable landing order and to set a target landing time for each aircraft, PACTAS supports the

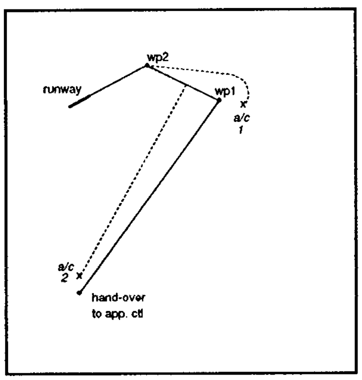


**Figure 12 : Expected Routes**

controller in achieving time based spacing of arriving aircraft. Notionally, the controller is presented with the predicted landing time of each aircraft, based on its expected route and expected vertical trajectory to touchdown, and a new prediction is made every time the aircraft's plot data are updated. The predicted touchdown time is compared with the target landing time to indicate a predicted touchdown time error. With this advice the controller is able to react positively to control aircraft so as to minimise error prediction and thereby land aircraft nearer to their target landing times.

An obligatory data entry requirement exists, that of telling the system of cleared heading changes. Airspeed data entry is optional, and in its absence the system compromises by using stored profile database values.

To determine the expected flight path PACTAS makes use of both controller imposed aircraft heading, and a notional route through approach airspace to the runway, in calculations that are repeated after each aircraft position update becomes known. Consider the two inbound routes shown in the Figure 12. The problem is to construct the expected routes, for the inbound aircrafts marked 'x', from their current positions to touchdown, upon which prediction calculations are made. The nominal route between entry-fix and runway is shown by the series of straight-line legs. In this example, it is assumed that aircraft 2 will continue on its present heading until intercepting the nominal route, as shown by the dotted line. Thereafter the standard route is assumed. For aircraft 1, the expected route includes an immediate turn towards the waypoint at the inbound end of this preferred trackline, (wp2 in this example). PACTAS contains logic which detects the significance of major heading changes such as occur when an aircraft is turned from a downwind path on to base leg. After the new heading is made known to PACTAS an intercept on the existing intercept leg may well be inappropriate and if that is so, it then looks along the route to the next standard track-leg to find an intercept.

As far as the speed profile is concerned, PACTAS takes account of a stored performance model for each type of aircraft. Part of this model describes the preferred speed profile from about 2500ft down to the runway as a function of altitude. Above this altitude the latest controller entered speed is assumed.

The Expected Altitude Profile is built taking into account that the aircraft will remain at high level for as long as possible, i.e. retaining current altitude until beginning an idle thrust descent so as to be level shortly (2 nm) before glideslope intercept. This is to allow the aircraft to fly without wing flaps extended for as long as possible, thus retaining the option to increase airspeed, whilst not precluding speed reduction, as a way of adjusting time.

A colour radar picture is displayed to the controller on a Plan View Display, presenting such information as extended runway centreline with distance to run marks, notional routelines and radar range rings at 5 nm intervals out to a range of 25 nm centred on the landing runway threshold. A three-line aircraft data-block is used. The two first are the usual ones, and the third one gives the Landing Sequence

Number of the aircraft and the currently predicted time error at touchdown, in seconds. The controller may display the expected flight plan of any aircraft as currently perceived by the prediction software. Making the appropriate touch interface entry causes the expected flight plan to be shown for about four seconds.

A touch sensitive EDD is used to control and direct the predictive service provided by PACTAS. Other functions include the silent acceptance and hand-over of aircraft, the adjustment of the PVD picture and requests for expected flight plans to be displayed on the PVD. Any data entry relating to an aircraft requires that the callsign (e.g. DLH928 in Figure 13) be first touched. This results in the EDD picture's changing as shown in Figure 13, where the selection of the speed (230 kts in this example) further modifies the EDD picture to allow a new speed entry. The speed selection, or heading selection, or both, are entered for PACTAS by touching the ENTER label, or the REJECT one if the transaction is to be aborted. The NEXT label is used for the automatic assignment of a standard heading corresponding to the next approach path leg. PACTAS can also help the controller in proposing when to turn an aircraft on to a new heading : if a new heading is selected and the PROBE label is touched before the data are entered, the

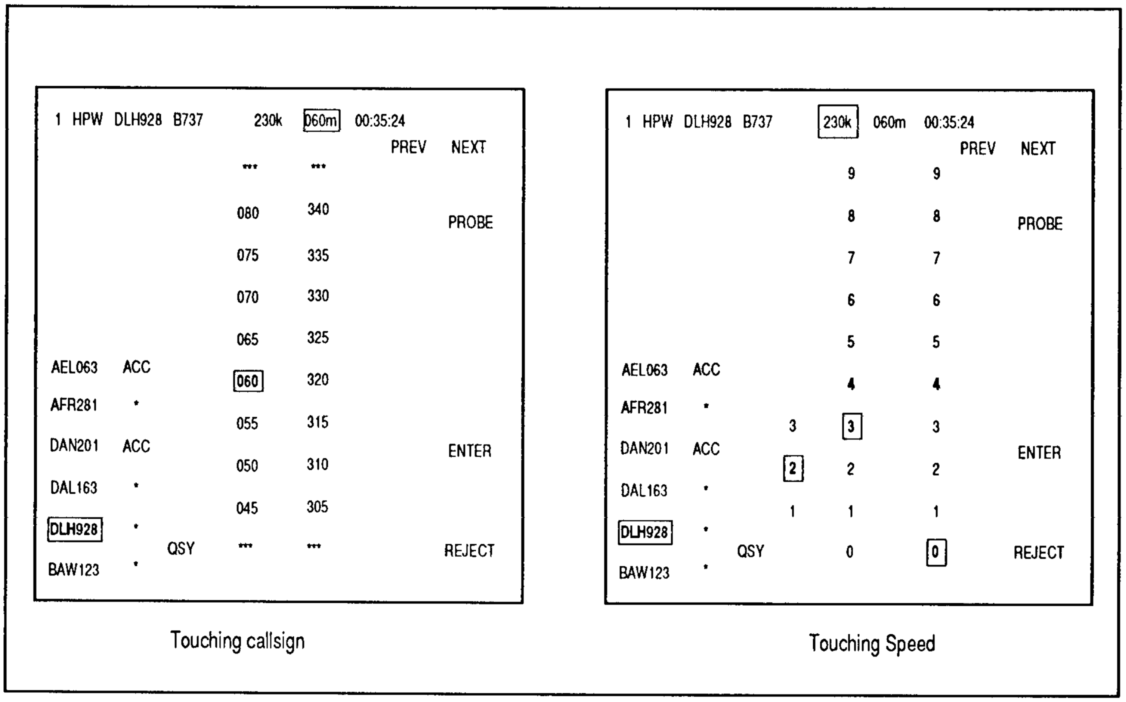


**Figure 13 : EDD pictures**

prediction starts with the old heading but assumes that the turn from old to new heading is just beginning. With each successive radar sweep, the predicted early time error would decrease, the interpretation being, "If the aircraft turns ***now*** on to the selected heading this will be the landing time error". By anticipating when to instruct the aircraft to start its turn, a few seconds before the time error display reached zero, an accurately timed instruction can be achieved. After turn instruction, because of the meaninglessness of the "old" heading probe, the controller has to cancel the PROBE option for that aircraft.

For experimental purposes, planning data preparation, including the allocation of Landing Sequence Numbers, allocation of runway times and the identification of planned entry fix times and altitudes has been incorporated into an off-line 'scenario generator' program. Traffic samples can be assembled to meet any specified arrival traffic density. 'Airborne' times for the sample traffic can be generated to support disorderly arrival at the entry fixes, to the experimenter's specification.

## VI. THE ZONE OF CONVERGENCE

The EUROCONTROL Engineering Directorate has been working since 1978 on the concept of on-line Air Traffic Management and aircraft guidance based on prediction and sequencing of aircraft trajectories.

The basic idea of the ZOC concept is to advise controllers in the en-route sectors and terminal manoeuvring areas (TMAs) on how to optimise, in terms of safety and cost efficiency, the traffic streams of an area extending some 100 to 300 nm from the runways. This is done by establishing a "planned flow", based as far as possible on "preferred" arrival times, and thereby determining a planning sequence. To achieve such a goal, the different functions required for handling such a problem have been gathered in different modules in the ZOC system.

The Zone Of Convergence approach consists of three main modules, viz:

A **sequencer/scheduler**, which establishes a target landing sequence and associated landing times on the basis of one or more criteria;

A **guidance and control** module, which generates the control advisories to achieve the planned sequence based on real-time radar data acquisition;

A **man/machine interface** designed to facilitate an ergonomic controller/system dialogue.

This ground-based 4-D guidance system integrates, for each flight, control over all phases of the entire part of the trajectory flown in the area. The control variables include the landing sequence, with adjustments of the departure

sequences, and a set of corresponding times of transit through the Zone. Use is made of the speed control range specific to each type of aircraft, supplemented whenever necessary by modifications to the geographical track, in particular close to the runway for the definition of base and final turn prior to ILS interception. The guidance directives are compatible with present-day R/T ATC communications, and exercises have recently been conducted using data-link operations between ATC centres and aircrafts.

**Sequencer/Scheduler module**

This module, called the *Regional Organisation of the Sequencing and Scheduling of Aircraft System* (ROSAS), maintains a proposed landing sequence by a dynamic sequencing and scheduling mechanism, constantly checking against actual traffic evolution. The main processing steps involved are shown in Figure 14. The system is triggered every time new radar data become available and if data for a newly entering aircraft are available, an estimate of its preferred flight profile is made. This profile is the one the aircraft would follow if it were the only one in the sky, based on airline companies'rules (e.g. minimum cost, speed profile, etc). On the basis of these preferred flight profiles a landing sequence is built, with a First-Come-First-Served-at-the-Runway rule, taking into account weight class separation matrix, conflict-free path on the localiser, restriction of overtaking on common path and controller off-route vectorisations. Subsequently, a landing time is assigned to each flight based on its position in the landing sequence, the estimated landing time of the first aircraft in the sequence, the minimum separation requirements on the localiser and the runway capacity possibilities (requests for accelerating an aircraft, which delay one or more following aircraft).

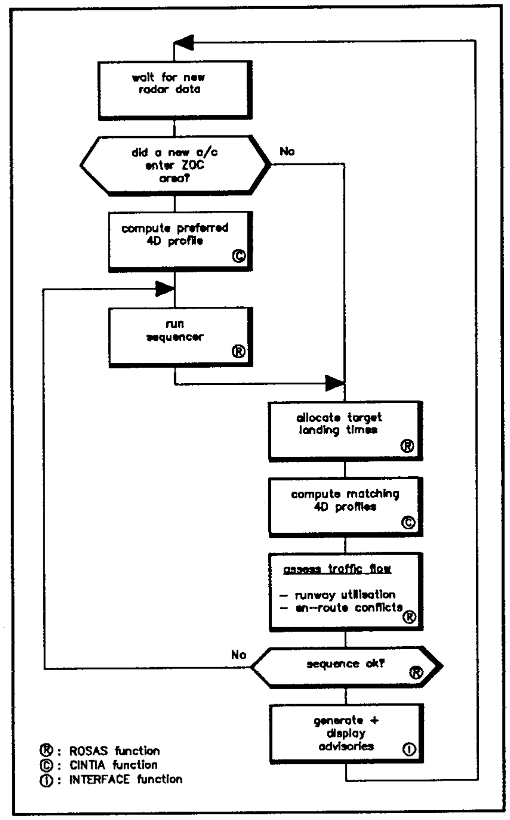


**Figure 14 : ZOC processing steps**

**Guidance and Control module**

Including the profile calculation and guidance and control functions, this module is referred as CINTIA (*Control of INbound Trajectories for Individual Aircraft*). It has to compute the "preferred" and the "actual" 4-D flight profiles, while endeavouring to obey the constraints defined by the sequencer/scheduler. In addition, it provides the sequencer with data on control range boundaries such as the "earliest possible landing time", etc. The CINTIA module has two main functions, a **predictor** and a **profile manager**, as shown in Figure 15.

The extended flight profile description (EFPD) comprises a composite set of information consisting of an exact description of every phase of the flight profile and the associated supporting data. Its basis is the standard ICAO flight plan defining, for example, callsign, planned route, cruise conditions and aircraft type. The EFPD is compiled from various databases, such as : preferred company operating procedures, standard instrument departure and arrival procedures (SIDs and STARs), current ATC constraints (allocated runway, etc), meteorological conditions (visibility limitations, etc), and aircraft performance data (EROCOA and PARZOC coefficients, etc).

The **predictor** constitutes the core of CINTIA. It computes the 4-D (latitude, longitude, altitude and time) flight profile on the basis of :

- the extended flight profile description;
- constraints from the sequencer/scheduler, if available;
- meteorological data;
- aircraft performance data.

The predictor starts a typical trajectory computation at the "end" constraints, i.e. the 4-D position at touchdown, and computes backwards to the current positions as observed by radar. Where the sequencer/scheduler has constrained the arrival time, steps must be taken to establish whether the time at the "start" constraint (i.e. current position derived from radar data) is met. Otherwise, the second CINTIA function is activated, namely the **profile manager**. The latter updates the extended flight profile description (EFPD) in the light of the observed discrepancies between constraints, computed trajectory and flight phase. Subsequently, a further check is made to establish whether the new flight profile is acceptable.

Effectively, the **predictor** and the **profile manager** are independent functions which interface through the extended flight profile description. The resulting sequence of flight phases is coded in a special "language" which can be directly interpreted by the predictor. The profile manager, for its part,

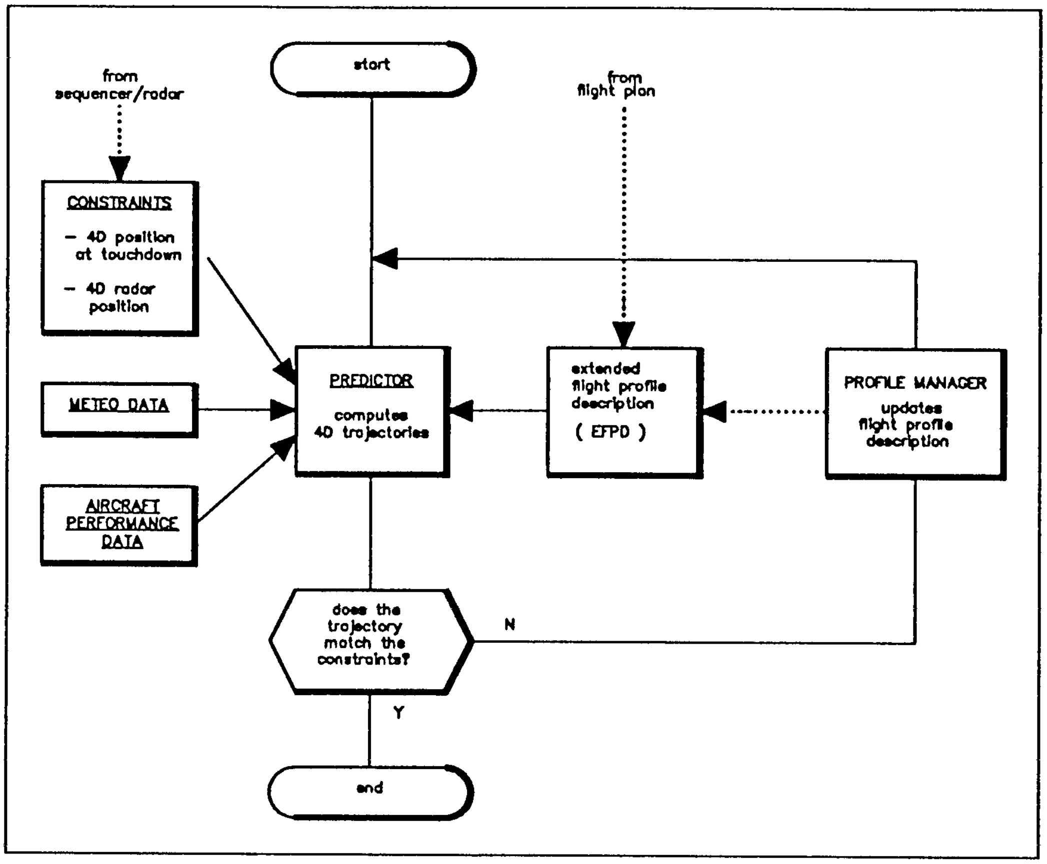


**Figure 15 : The CINTIA module**

tries to maintain a careful balance between the maximum range of possible arrival times available at entry into the ZOC and the retention in the later phases of the flight of sufficient flexibility, to be able to retain the capability to accommodate perturbations during the flight. This is why the differentcontrol variables accessible to the profile manager (speeds, flight levels, Top Of Descent points, distances to be flown on the localiser, baseleg headings, etc) are flight-phase dependent.

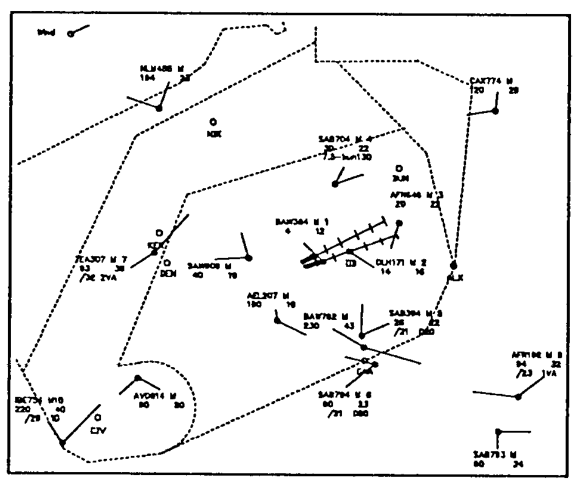

**Figure 16 : ZOC radar screen**

**Controller Interface**

Because of the dynamic characteristics of the ZOC concept, all flight plan deviations, whether triggered by controllers or by pilots, are automatically considered in the advisories generated on the basis of the observed radar tracks. This has virtually eliminated controller inputs to the ZOC system, leading to minimal changes in existing controller work positions. So, in principle, the ZOC interface is a machine-man monologue.

CINTIA generates control advisories for application on two levels, namely **Executive Control Advisories** and **Advance Warning Advisories**. The **Executive Control Advisories** pertain to the current suggested clearance and are displayed in a spare line of the standard radar label for each inbound flight (Figure 16). They may include the current valid speed advice or the specification of a radar vector. An example of a classical sequence of messages for an inbound flight is shown in Figure 17, where the highest time critical messages

(alerts) are displayed in red on a colour screen (shadowed area) or blinking on a monochrome display. At any time, the advisories reflect for each individual aircraft, whether or not

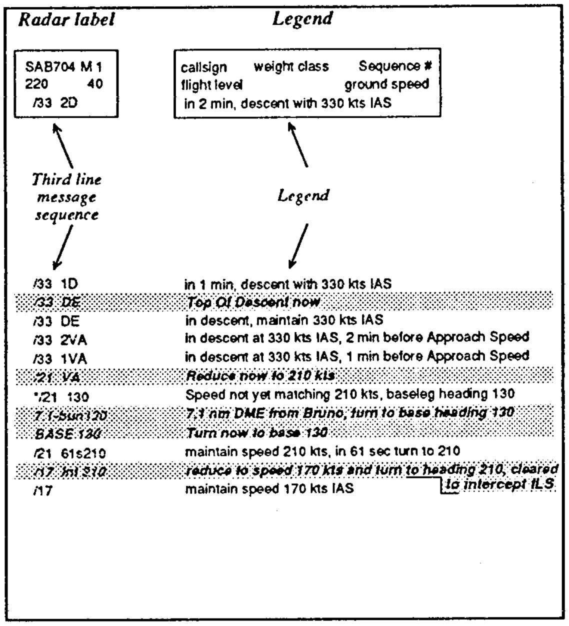


**Figure 17 : ZOC Executive Control Advisories**

respecting its predicted flight profile, its "current preferred constrained" flight profile, with CINTIA updating the advisories whenever necessary to take into account the actual situation.

The **Advance Warning Advisories** show the "executive control advisory" for the **next** control action. For example, when the executive control advisory suggests a cruise speed, the advance warning advisory displays the remaining flight time to the top of descent and the expected descent speed. Obviously, as the latter messages have a lower priority, they are usually collated in a table and displayed on a separate EDD or on an unused part of the screen.

On request, other supporting information is available to the controller via two different kinds of command, using a pointing device such as a mouse or a trackball, or a keyboard:

**Extended ZOC information :**

- Request for the number of Track Miles to Go, replacing the display of the ground speed;
- Visualisation of the ground projection of the planned trajectory;
- Visualisation of a 3 nm separation circle;
- Introduction of Cleared Flight Level, displayed afterwards close to the actual Flight Level;
- Acknowledge of alert messages, to turn them back to the label colour;
- Swapping of two aircraft in the sequence.

**Screen management :**

- Screen zooming in and zooming out;
- Rotation of the radar label around the aircraft position;
- Changing of sector visualisation;
- Removal of the third label line containing the advisory;
- Removal of the beacon names;
- Removal of the speed vector.

A Simulation facility for a Total Air Navigation System (STANS) has been developed in order to reduce the need for full-scale ATC facilities and to allow for accurate representation of the air component (ACCESS flight simulator capabilities). It constitutes a tool enabling a complete ATC system to be simulated, incorporating ground-side:

- flight plan, radar and meteo data processing;
- advanced on-line traffic management and guidance of flight functions;
- human role and related interfaces at several levels of automation.

Air-side, the simultaneous integration of various models or data such as :

- real aircraft data,
- full-scale flight simulators,
- ACCESS flight simulators in manual mode, semi-automatic mode, or both.

This environment makes it possible to develop, test, validate and assess any particular component with the actual or desired traffic density.

## VII. THE TIMER SYSTEM

TIMER, *Traffic Intelligence for the Management of Efficient Runway-scheduling*, is a time-based ATC concept designed to improve the efficiency of extended terminal area operations (en route approach, transition, and terminal flight to the runway). TIMER integrates en route metering, fuel-efficient cruise and profile descents, terminal sequencing and spacing, together with computer-generated controller aids, in order to maximise the use of runway capacity and improve the efficiency of delay absorption. The principal operational features of the TIMER concept are shown in Figure 18. The major steps in the system's operation are as follows:

1. The arrival stream into the extended terminal area is derandomised at the horizon of control by the establishment of a proposed aircraft landing sequence and a list of aircraft Scheduled Landing Times (SLTs) based on separation criteria. The desired metering-fix time as a result of the assigned landing time is also determined.

2. Nominal estimated times of arrival used in step 1 are based on representative aircraft performance models. By reference to these models and

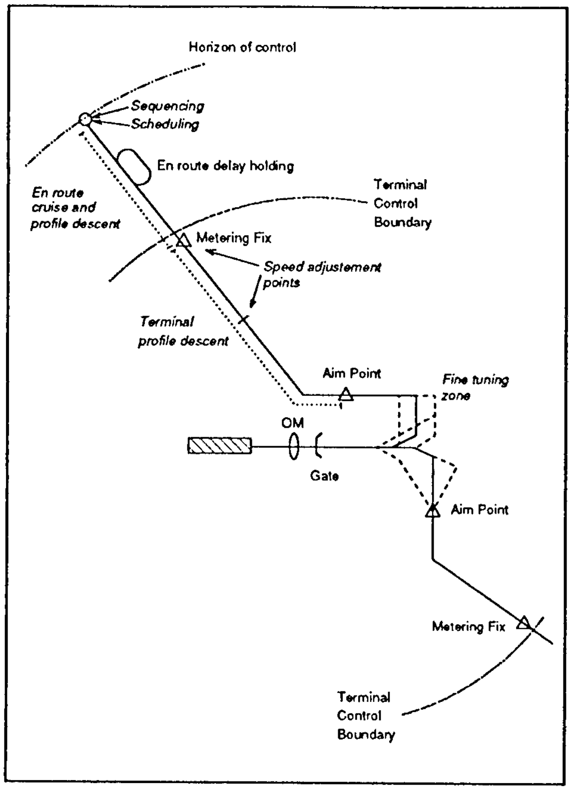


**Figure 18 : TIMER sequence of events**

predicted winds, a ground-computed trajectory is determined to meet the aircraft assigned scheduled landing time.

3. Computer-generated assistance is given to the controller to help him meet aircraft target times based on the trajectory calculations. The parameters determined are the en route cruise speed, the time to initiate and the Mach/CAS speeds required to fly a flight-idle-thrust descent, and the terminal segment speeds and headings.

4. Adjustments to the scheduled landing times and, if necessary, changes in the landing sequence are made to accommodate errors and anomalies in factors such as wind, navigation, airspeed, and heading which affect the SLT of either the aircraft in question or the preceding aircraft. These scheduled adjustments or controller-action points occur at the following points shown in Figure 18 : the metering fix, the speed adjustment points and the fine-tuning region. The landing sequence is fixed before aircraft arrive in the fine-tuning region.

5. The aircraft trajectory is fine tuned in the final-approach region in order to meet the aircraft's final scheduled landing time with limited time error.

To be more precise, the landing sequence is built using the aircraft's undelayed Estimated Times of Arrival (ETAs), which are based on nominal arrival speeds, route segment distances to the runway and predicted winds. Currently the sequencing criterion used is a projected first-to-reach-runway ordering. Starting at the horizon of control, there is a range of earliest and latest landing times that the aircraft can achieve by varying its speed between nominal approach values and the slowest possible speeds imposed by performance considerations. If the landing time assigned exceeds the latest attainable speed-control time, the additional delay will be absorbed by path stretching inside the TMA or en route holding.

The flight path is divided into a cruise segment and several descent and level deceleration segments. The times and distances associated with all these segments are calculated from aircraft type specific point-mass equations of motion for a clean configuration. An iterative process is used to determine the required metering fix altitude and the resultant time, based on the aircraft's SLT, the aim point (location where clean idle descent ends) and the nominal speeds for the approach segments. Another iterative process calculates the cruise Mach, the Mach/CAS descent speeds and the time at which the descent should be started so that the aircraft meets the metering fix conditions in terms of time, altitude and speed.

The aircraft's SLT may be changed when it arrives at the metering fix either because of the effect of preceding traffic or because of the aircraft's own metering fix time error. Depending on circumstances, the SLT may be slipped forwards or backwards, or the landing sequence may even be altered if the scheduled slippage warrants such action. Using the aircraft's updated landing time based on its actual metering fix arrival, the trajectory calculation determines the terminal profile descent speeds needed to meet the target time.

Within the TIMER fine-tuning region the computer-aided manoeuvres consist of timing both the turn-to-base and the turn-to-final manoeuvres. This process is based on a regularly updated ETA calculation that displays how much in advance of its SLT, the aircraft would be if its turn instructions were issued immediately. The difference between the SLT and the ETA is referred to as the direct-course error (DICE) value.

The TIMER-generated commands are presented as part of the alphanumeric data block associated with each aircraft. These data blocks are composed of 10 fields of text as described in Figure 19. Field 1 is used to display the DICE value decreased at a rate dependent on the ground track and speed of the aircraft. Field 7 displays the recommended heading and field 8 the recommended airspeed. Fields 9 and 10 provide time reference information with respect to the time at which the command should be delivered, the Command Delivery Time (CDT). The display of this CDT gives the possibility of compensating for delay in delivery in the command. For example, if TIMER generates a turn instruction to a given heading and the controller is too late in transmitting the command, a turn with a "compensate"

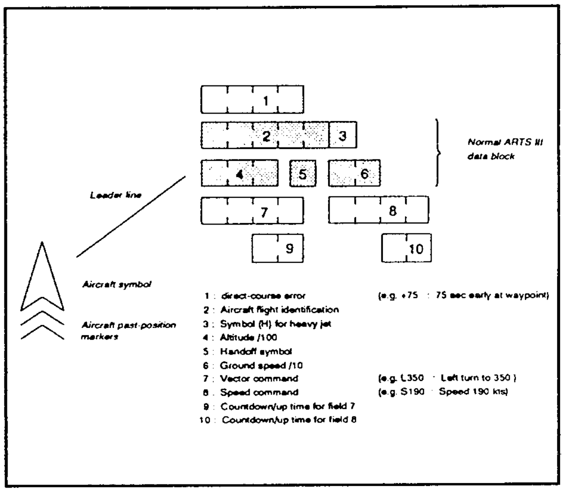


**Figure 19 : TIMER data-tag fields**

heading might be issued instead if the controller judges that necessary for compensation. The controller might afterwards disable the command by use of an electronic data tablet and an associated pen.

This environment was used to make a parametric sensitivity analysis, and was integrated into the Terminal Area Air Traffic Model (TAATM) simulation so the effect of

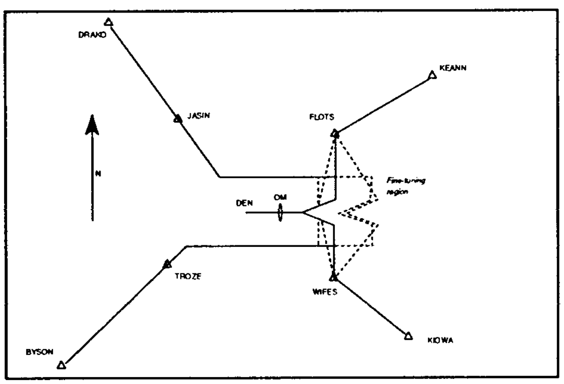


**Figure 20 : Denver Airport 26L approaches**

significant parameters could be studied. The TAATM is a flexible dynamic model of the airborne, navaid, ground control, and communications aspects of the terminal area environment which can be run either in fast-time (without controller/pilot interactions) or in real-time (with human interactions). The Denver Stapleton approach routes operating in a runway 26L landing configuration were used with IFR commercial arrival traffic (see Figure 20). The Langley DC-9 Full-Workload Simulator cockpit provided the vehicle for airline crew interaction. The computer data interfaces, voice links and controller workstations of the Langley Mission Oriented Terminal Area Simulation (MOTAS) facility linked the TIMER algorithms and cockpit simulator interactively. The major elements of the MOTAS facility are an airport terminal area environment model, several aircraft models and simulator cockpits, four pseudo-pilot stations, two air traffic controller stations, and a realistic air/ground communications network. In addition, it can be linked to the NASA Wallops Flight Facility by telephone data communication lines or satellite to allow interaction with live aircraft for actual flight tests.

## VIII. THE NASA CENTER/TRACON AUTOMATION SYSTEM

An automated air traffic control system based on a hierarchy of advisory tools for controllers has been developed at the NASA Ames Research Center. The design of this system comprises three interconnected subsystems, referred as the *Traffic Management Advisor* (TMA), the *Descent Advisor* (DA), and the *Final Approach Spacing Tool* (FAST). Each of these subsystems provides a collection of tools for specific controller positions and tasks: the Descent Advisor provides automation tools for managing descent traffic, the Traffic Management Advisor generates optimum landing schedules, and the Final Approach Spacing Tool allows the Tracon controller to choose interactively various levels of automation and advisory information ranging from predicted time errors to speed and heading advisories for controlling time error.

The different functions of these modules are spread over the whole Center/Tracon control team, as illustrated by Figure 21.

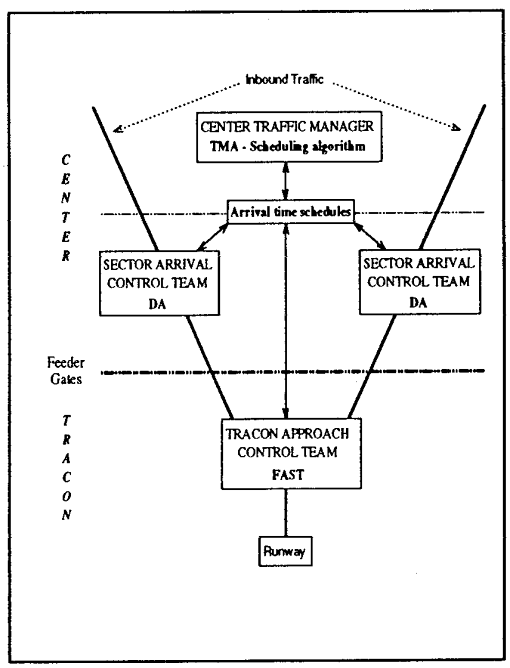


**Figure 21 : CTAS automation modules**

The primary function of TMA is to plan a landing order and

to assign spaced landing times to all arrivals. These time schedules are generated while aircraft are 150 to 200 nm from the airport. The TMA algorithm plans these times in such a way that traffic approaching from all directions will merge on the final approach without conflicts and with optimal spacing. The TMA also assists the *Air Route Traffic Control Center* (ARTCC) Traffic Manager in rerouting traffic from an overloaded sector to a lightly loaded one (gate balancing) or in the event of major disruptions such as runway reconfiguration or weather disturbances. In general, the functions of the TMA involve assisting the Center Traffic Manager in co-ordinating and controlling the traffic flow between Centers, between sectors within a Center, and between the Center and the Tracon facility.

The Descent Advisor is designed to provide Center controllers with flexible tools to implement the traffic plan generated by the TMA. For all aircraft entering an arrival sector, the DA implemented at that sector computes *Estimated Times of Arrival* (ETAs) at its respective arrival gates. This ETA computation takes into account the airspace structure and ATC procedures for each arrival sector. Only two DAs are shown in Figure 21, but the number varies according to the terminal area structure. The ETAs from all arrival sectors are sent as input to the TMA, which uses them to calculate the *Scheduled Times of Arrivals* (STAs) at the runway. These STAs are then transformed by the TMA to gate arrival times by subtracting the time needed to fly from the gate to touchdown, and are sent to the DAs at the appropriate arrival areas. The DA uses these STAs to generate cruise and descent clearance which controllers can use to keep aircraft on schedule. For aircraft that drift off their planned time schedules, the controller can request revised clearances that correct such time errors to the extent possible.

The Tracon controllers take over control of traffic at the feeder gates. They merge the traffic converging on the final approach path while making sure that aircraft are properly spaced. The FAST assists the controller in making any corrections with high accuracy and a minimum number of heading vectors and speed clearances. Achieving precise spacing between aircraft on final approach ensures that landing rates will always be close to the theoretical capacity of the runway.

**Design and graphic interface of the TMA**

The Traffic Management Advisor comprises algorithms, a graphic interface and interactive tools to be used by the Center Traffic Manager. The TMA uses the concept of a **Scheduling Horizon**, which is the time interval specified by the traffic manager to determine when an aircraft is first added to the list of aircraft currently being scheduled. The aircraft's STA becomes frozen when its ETA crosses the **Freeze Horizon** defining, together with the Scheduling Horizon, the **Scheduling Window** where an aircraft becomes eligible for sequencing on the basis of its updated ETA. Four scheduling techniques may be selected by the user. They are referred to as First-Come-First-Served (FCFS) without time advance, FCFS with time advance, Position Shift without time advance and Position Shift with time advance, a position

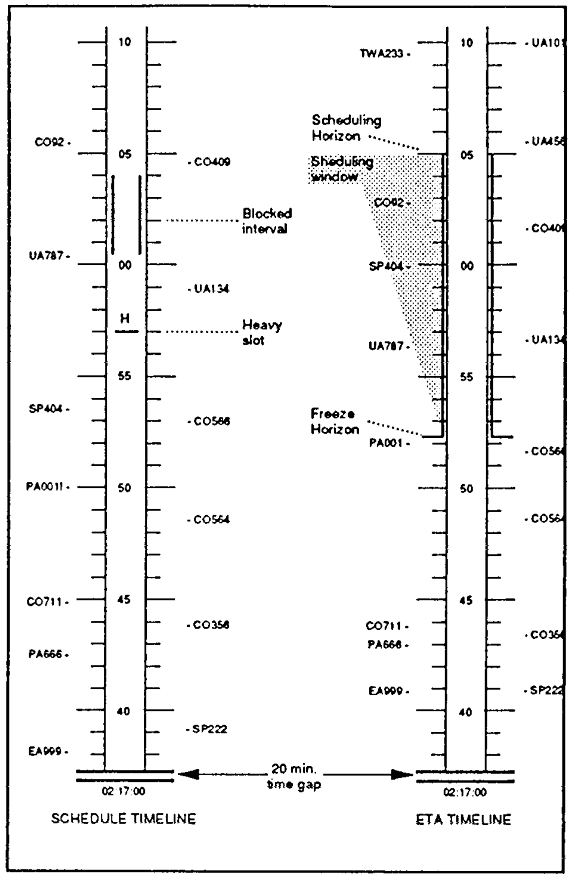


**Figure 22 : Time lines for flow monitoring and manual scheduling**

shift being a possible aircraft sequence position shift to allow aircraft of the same weight class to be grouped together. The traffic manager is also allowed to use **Blocked time intervals** in order to handle cases such as temporary closure of the runway; reservation of time intervals for takeoffs and emergencies; or **Blocked time slots** to reserve a time slot for an aircraft not tracked by the Center radar, but expected to land at the specified time. Figure 22 shows how the traffic manager, using a pointing device such as a mouse, can interact with time lines. He may alter the scheduled time of any aircraft currently in the system by dragging an aircraft tag on the desired position on the time line. Figure 22 shows only a labelled part of one of the different windows displayed on the traffic manager's screen. There is also an overview of the traffic in the Center on a miniature PVD, and information about the status of all the DAs providing ETA data and receiving STAs from the TMA. The various scheduling parameters such as airport acceptance rate and the configuration of the time lines are also presented on this screen.

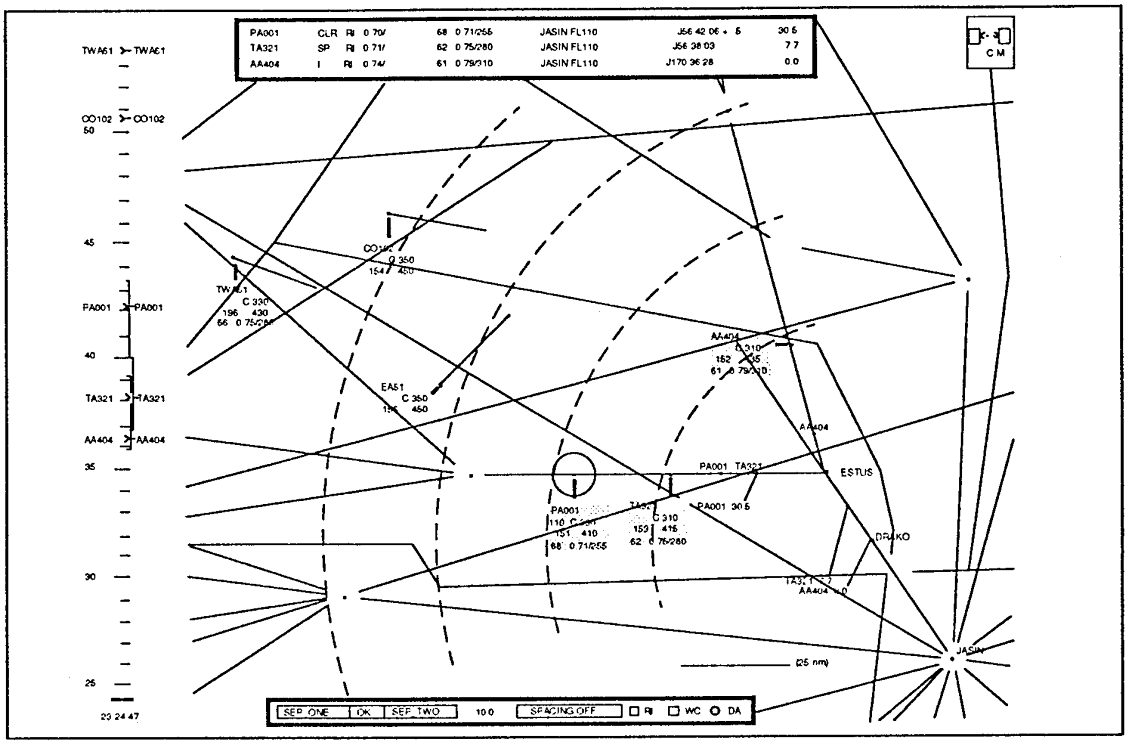


**Figure 23 : Controller display with DA advisories**

**Design and graphic interface for DA automation tools**

The analytical foundation for the DA is a collection of numerical algorithms for the accurate prediction and control of aircraft trajectories in space and time, referred to as four-dimensional guidance. It was shown [Ref. 30] that with descent clearances generated by these algorithms, pilots could control arrival time at a feeder gate with an accuracy of within 20 sec. One major challenge of applying this in an ATC environment lies in the design of an efficient interface between the controller and the algorithm. The controller interface combines on a single high resolution colour monitor both the traditional plan-view display of aircraft tracks and advisories generated by the automation tools. Figure 23 illustrates the detailed implementation of this concept for an arrival area at the Denver Center. Specifically, the picture shows a plan-view map of the airspace through which arrival traffic flows towards the Drako feeder gate (see also Fig. 20, preceding chapter), one of the four gates feeding traffic to Denver Stapleton International Airport. The standard arrival routes leading through the gate into the Tracon are normally colour distinguishable from other air routes, sector boundaries and other map features. A complete set of display management tools including zooming and panning has also been implemented.

Aircraft position data-blocks are organised in standard format, with the second line showing mode C altitude in hundreds of feet, and the third line the computer identification code and the ground speed in knots. There is an additional time line on the left of the screen, showing the ETAs for the different aircraft to the time control waypoint, in this case Jasin. The scale covers a time range of about 30 min. Selecting an aircraft causes two panels to pop up on the screen. At the top of the screen, the **DA Clearance Panel** displays profile descent information generated by the DA algorithm (3 aircraft selected in Figure 23). For convenience, these parameters (desired cruise speed, the DME range of the Top Of Descent and the descent speed profile) can also be displayed on an extra line in the aircraft data block. The **Mode Select Panel** near the bottom of the screen provides access to the different constraints possible by generating speed profiles and ground tracks for time control approaches. These will be discussed later.The selection of an aircraft also causes the display of a **Time range bar** on the ETA time line and a **Top Of Distance marker** and **Distance spacing markers** on a selected waypoint on the DA-generated trajectory. The time range enclosed by brackets indicates the maximum variation of arrival time achievable through speed profile management along a fixed arrival route. The spacing markers can be used to probe quickly for conflicts at various points on the arrival routes. For example, the controller can check for conflicts at critical route junction points such as *Estus*, as well as at *Drako* or at the time control point, *Jasin*.

As already described, a time range bar appears on the ETA time line for a selected aircraft. This allows the controller to move the aircraft tag within those limits, which activates the

DA algorithm for the generation of new descent parameters displayed in the DA Clearance Panel. At that time, the profile mode designator is changed from SP (Standard Procedure profile : current cruise speed at the current altitude and descent at idle thrust to the altitude specified at Jasin) to I, which stands for "Inquiry", and the TOD and spacing markers are also updated. When the controller has found a profile with a conflict-free arrival time, he can lock the profile and clearance, which stops the cyclical renewal of the profile and changes the profile type designation from I to CLR (cleared). This locked profile mode is illustrated by PA001 in Figure 23.

In the traffic management concept described earlier, optimum landing times are generated by the TMA. The controller accesses the automatic scheduler, referred to as the TMA mode, by a keyboard command. In this mode the different ETAs shown on its time line, are replaced by the corresponding SLTs allocated by the TMA. If necessary, however, the controller can still assign his own gate times by returning the DA to the manual mode, which obviously also requires verbal co-ordination with the other Center controllers.

The Mode Select Panel also displays which constraint on the speed profile the DA algorithm has used in the generation of new descent parameters and associated advisories. Three different modes have been implemented and are referred to as Cruise (C), Descent (DA) and Cruise-plus-Descent (C+D), according to the speed phase(s) the DA algorithm could iterate on, which are respectively the cruise speed, the descent speed, or both cruise and descent speeds, to achieve the specified arrival time at the feeder gate.
The controller can also choose via the Mode Select Panel two different modes to generate descent clearances that meet specified spacing distances at the time control point : **SEP_ONE** and **SEP_TWO**. For two selected aircraft and for a desired spacing distance (10.0 nm in Fig. 23), the SEP_ONE mode should be chosen to modify only the speed profile of the trailing aircraft. On the other hand, the SEP_TWO mode gives the DA algorithm the freedom to change the speed profiles of both trailing and leading aircraft.

Two horizontal guidance modes, referred to as Route Intercept (RI) and Waypoint Capture (WC), are also available to the controller to recommend efficient horizontal paths for both on-route and off-route aircraft which have to meet time-constrained arrival at the feeder gate.

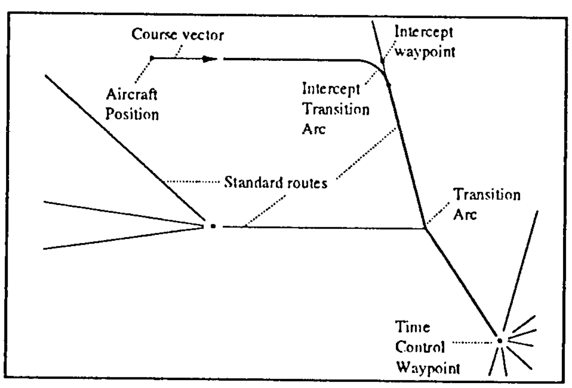


**Figure 24 : Route Intercept guidance**

In the **Route Intercept** mode, the DA algorithm seeks to create an RI segment based on straight line and arc, connecting the current aircraft position to a point on a standard route segment. This RI segment will be added to the segments of standard route traversed between the RI point and the time control point, in order to generate speed and altitude profiles in exactly the same manner as if the new route were a standard one.

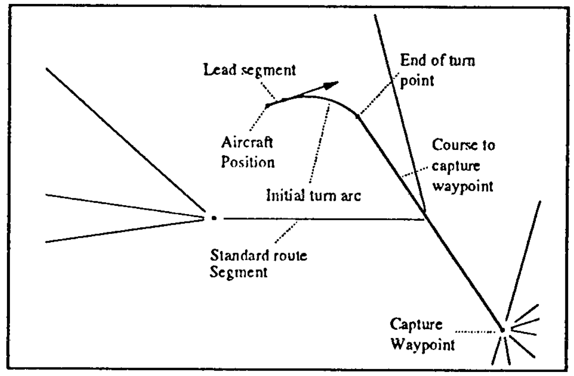


**Figure 25 : Waypoint Capture guidance**

The **Waypoint Capture** mode provides advisories for predicting and controlling the arrival time of an aircraft during off-route vectoring. It uses only the aircraft's initial position and course and the capture waypoint position in generating the horizontal path. Therefore, it differs from the RI mode in that it does not depend on the knowledge of standard arrival routes for its calculation. The horizontal path synthesised in this mode consists of an initial circular arc turn starting at the current position and course followed by a straight line to the capture waypoint. Once this logic has determined the parameters of the path, the DA algorithm synthesises the speed and altitude profiles in exactly the same way as in the RI mode, and displays the current heading advisory at the End of Turn point. The most sophisticated application of this mode lies in advising the controller when off-route aircraft should be vectored towards the capture waypoint in order to capture a time slot at the time control waypoint. This includes solving the related problem of when to break out of a holding pattern to capture a time slot.

The controller normally "locks" a profile immediately after issuing an aircraft with the clearances displayed in the DA Clearance Panel. When a profile becomes locked, the DA algorithm ceases to generate new profiles and initiates tracking of the locked profile. The **Profile Tracking** process consists of computation of errors in time, lateral position and altitude between the current position of the aircraft and the locked profile. This process first checks to establish whether the aircraft position lies within a three-dimensional corridor centred around the locked profile, otherwise the aircraft is

considered to be off track, and the rest of the error computations are skipped. If the aircraft position is within the route corridor, it determines the increment or decrement in current time needed to get back on to the locked profile. The time error, in seconds, is displayed in the DA Clearance Panel to the right of the locked profile arrival time. It is also incorporated in the position of the predicted arrival time along the time line via the algebraic addition of the time error to the locked profile arrival time.

A **Conflict Detection Tool** searches for conflicts along complex 4D descent trajectories as far as 30 min. into the future. In order to keep the computation time for conflict detection within acceptable bounds, the algorithm incorporates two simplifying conditions. First, conflict checking is performed only for those pairs of aircraft in which at least one aircraft of a pair is a "selected" aircraft. The second simplifying condition is to include in the conflict check only those aircraft whose ETAs at the time control point are within 5 minutes of the ETAs of any particular selected aircraft. The criteria for loss of minimum separation are defined in terms of horizontal and vertical distances, specific to either Center or Tracon regulations. Overflights are also included in the conflict check with every selected aircraft. Since 4D descent trajectories are not computed for overflights, the conflict detection algorithm first creates a pseudo 4D trajectory of 20 min. duration. Then, the algorithm treats the overflights in the same way as it does descent aircraft. Three types of symbols are used to warn the controller that a conflict has been detected : a red star on the position of the future conflict, the ID tags of each pair of aircraft in conflict turned to red, and a pop-up window displaying for each pair of aircraft in conflict their callsign followed by the time in minutes to the initial point of separation violation.

### Design and graphic interface of the FAST

The TMA initially generates schedules for all arrival aircraft while they are still in ARTCC airspace. If the traffic flow remains relatively smooth and uninterrupted, aircraft will arrive at feeder gates with little or no time error. In this case, the STA will remain unchanged by the Tracon Scheduler. If, however, some traffic arrives with a significant time error for various reasons, both a Scheduling and a Freeze Horizon are implemented within the Tracon, typically set at 11 min and 8 min to touchdown, respectively. Once a STA, revised or not, has been defined, the trajectory synthesis algorithm is used to compute the 4D path that meets the STA generated. This algorithm is in fact a modified version of the ARTCC DA, described previously. All the automation tools available may be used here in "fine tuning" traffic. The Horizontal Guidance modes here are ideal for either extending or compressing the downwind leg of the approach path or varying the intercept of the final approach course. Handling of popup aircraft or missed approaches also becomes very convenient with the combination of these guidance tools with the time line display.

## IX. THE MITRE CORPORATION GHOSTING AID.

Many research works in our area of interest have been undertaken in recent years at the Air Transportation Engineering Division of the MITRE Corporation. They have yielded a thorough appreciation of the kind of problems facing Terminal Automation. MITRE was recently asked by the U.S. Federal Aviation Administration to adapt different tools, in conjunction with the MIT's Lincoln Laboratory, for the U.S. air traffic control system. The Ghosting Aid is one of the research projects undertaken at MITRE itself. It is an automation aid designed to allow two streams of aircraft to be safely controlled when approaching converging runways.

In such cases, a specific time or distance relationship is to be maintained between aircraft, in order to avoid their arriving simultaneously at some point of concern (e.g. the missed approach point). Precise staggering would nevertheless be required to realise the full capacity benefits of staggered converging approaches. Staggering also requires co-ordination between controllers, which adds to the difficult, of the task.

The design approach for the aid is to convert the converging approaches geometry to simulate a single runway approach geometry. The proposed aid is a simple display concept illustrated, together with its basic algorithm, in Figure 26.

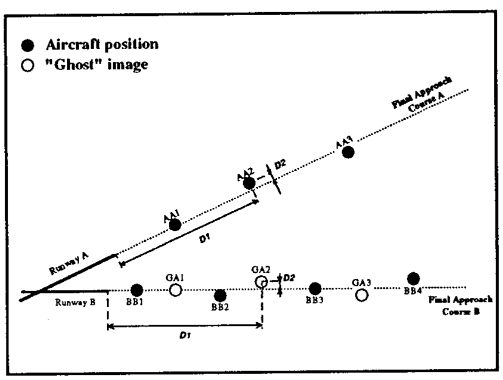


**Figure 26 : Ghosting Aid display concept**

AA1, AA2 and AA3 are the callsigns of aircraft on final approach A and BB1, BB2, BB3 and BB4 are callsigns for aircraft on final approach B. GA1, GA2 and GA3 are reference images of aircraft AA1, AA2 and AA3 respectively along approach B, so that the distance of the reference image $GA_i$ from runway threshold B is equal to the distance of aircraft $AA_i$ from runway threshold A. The reference image is thus a virtual aircraft symbol or a "ghost image". The "stagger" is the difference between aircraft distances and their respective runway thresholds. Figure 26 shows that the stagger distance between two aircraft $AA_i$ and $BB_j$ is the same as the distance between $GA_i$ and $BB_j$. As aircraft progress on approach A, their "ghost images" progress by the same amount.

The immediate application of this concept is expected to be for airports where both runways of the desired converging approach configurations are equipped with an Instrument Landing System (ILS). However, the display concept can be extended to other approaches and is expected to accommodate a large variety of navigational environments including advanced navigation such as the Microwave Landing System (MLS).

The concept, which does not require any new surveillance or navigation equipment, is also expected to be useful for application in any other merging situation in ATC, e.g. in en-route airspace.

The prototyping activities were conducted in MITRE's Terminal Area Simulation Facility, and the outcome has been the definition of the functional design of this automation aid for coding into the ARTS-IIIA system for field evaluation at St. Louis International Airport.

## X. TERMINAL AIR TRAFFIC CONTROL AUTOMATION

Under the *Terminal Air Traffic Control Automation* (TATCA) program, the Federal Aviation Administration has established the basis for the compatible integration of a number of promising automation aids that have been investigated over the years. The FAA asked the Massachusetts Institute of Technology's Lincoln Laboratory to serve as system integrator for this programme. The concepts under developments by NASA, the MITRE Corporation and European agencies were to be examined and, where appropriate, integrated into a proposed advanced system for terminal air traffic control.

Amongst the projects relating to this topic (*Parallel Runway Monitor, Airport Surface Traffic Automation, etc*), there is one of particular interest, the aircraft trajectory prediction for Terminal Automation, integrated into a Dynamic Time-Based Planning (DPT). The TATCA programme has been studying the use of improved sequencing and timing to increase the landing rate at major airports, especially under Instrument Meteorological Conditions (IMC). This has been accomplished by developing a plan for the efficient flow of traffic in the terminal area that provides advisory information to controllers to help them achieve the planned timings.

The main objective of the TATCA plan is to ensure that landings are spaced as closely as possible, without violating separation standards or operational requirements. To maximise its effectiveness, the plan will extend into the en-route facility that feeds traffic to the terminal. Within the limits of operational constraints, TATCA will increase the efficiency and throughput of terminals, by adapting the delivery rate to the constantly changing terminal environment. The principal automation functions being investigated for the achievement of this goal are the following : traffic planning and controller co-ordination aids, speed-control and holding advisories, descent advisories (top-of-descent point and descent profiles), and final approach spacing aids. The outputs of these automation functions will be presented to individual members of the terminal controller team in the form of co-ordinated graphic displays.

### Trajectory Prediction Software Structure

It employs a layered modular structure to maximise its flexibility and to facilitate the addition of new flight modes or the modification of existing modes, such as descending, decelerating, turning, or following a fixed glideslope. In the lowest layer are a set of aircraft performance models which calculate lift coefficient, required flap position, drag and thrust limits using polynomial approximations and table lookup of performance data specific to each class of aircraft. The middle level contains algorithms specific to each mode of flight that use an aircraft performance model and atmospheric characteristics to predict how the aircraft would move if it were flying in a specific mode based on a point-mass model of the aircraft's dynamics. The highest level contains routines that use the lower level algorithms and models to piece together trajectories out of various modes and to perform the calculations required by the automation logic. The middle-level algorithms used for the simulation of different modes of flight are not constrained to use the same integration procedure, because of the choice of the most appropriate integration variable.

### Dynamic Time-Based Planning

The planner is supplied with information on the radar positions of aircraft, their flight plans, the weather and the runways in use. Supervisory personnel adjust certain parameters of the logic to match the conditions of the moment and the capabilities of the personnel on duty. When a new arrival aircraft appears, the planner uses the algorithms described previously to determine how that aircraft can best be sequenced and merged with traffic arriving from other directions. The flight path and fix crossing times that result become part of the overall plan for traffic flow in the terminal area. Each control position in the terminal and adjacent en-route sectors is provided with an extracted part of this traffic plan that applies to its sector. In the final a approach zone, the controller is provided with indications guaranteeing precise and efficient spacing. The traffic plan is constantly being adjusted according to the actual progress of aircraft and changes in terminal conditions. Some of these changes will occur gradually and, from the controller's point of view, almost imperceptibly. Other changes, such as the creation of a landing slot for a missed approach, will require a sudden and noticeable change in the traffic plan and must be clearly announced and co-ordinated with the control personnel involved.

### Conformance Indications and Control Advisories

Such indications show the extent to which aircraft are ahead of or behind plan. A second step beyond the simple display

of conformance is to provide controllers with assistance in keeping aircraft in conformance with the plan. As an example of how such assistance may be implemented, a speed control advisory is currently being developed in the TATCA simulation of the Boston terminal area. Information can be presented either on an auxiliary display or on the radar scope itself. Tests are being conducted on a time-line auxiliary display, of which the format is similar to the display being installed as part of the COMPAS system at Frankfurt (see Fig. 6, chapter II). This display can provide the aircraft sequence, merge order, landing times/sector exit times and time conformance. Other aircraft-specific information, such as holding stack management information or current speed assignment, can be provided on this display together with callsigns. Time-critical information, such as control advisories, will appear directly on the radar scope.

Terminal automation systems must also allow supervisory personnel to retain control of the strategies and the overall traffic loading in the terminal area. This is why these positions are provided with special displays enabling them to configure the automation tools, enter directives to modify the strategy of the planner, or establish desired traffic flow rates. They provide a broader overview of the traffic and allow supervisors to look at alternative future scenarios based upon different runway configurations or traffic flow rates. A version of the supervisory display is also being tested at the Lincoln Laboratory. Four display windows allow the supervisor to view the wind at the airport, the ceiling and visibility, the airport configuration and the traffic loading.

### Final Approach Timing Aid (FATA)

This final approach timing aid uses the predictive capability of computers to indicate the optimum parameters for the standard turns preceding intercept of the Instrument Landing System (ILS) in order to achieve more precise spacing on final approach,especially under IMC conditions. TATCA works by refining FATA display formats and designing a sound operational context for the use of FATA. Among the key design issues being addressed are the manner in which the logic will adapt to visual separation practices, the manner in which the missed approach rate is controlled, the process for predicting aircraft landing speeds, the buffers required to ensure that separation standards are observed, and the Human-System Interface (HSI).

### Field Evaluation Plans

The initial field test will be accomplished by introducing the planner as an auxiliary capability at an existing Automated Radar Terminal System (ARTS). Radar and flight plan data will be extracted from existing computers and communications lines by means of non-interfering monitor connections. The automation algorithms will reside in an auxiliary workstation computer, and its display will support the supervisor functions. Information to be displayed to radar controllers will appear either on existing auxiliary displays or on the radar console, with no increase in the computational loading of the operational ARTS equipment.

## XI. M.I.T. FLIGHT TRANSPORTATION LABORATORY STUDIES

It is not the aim of this paper to cover the numerous topics of all the reports, theses and memoranda published by this department of the Massachusetts Institute of Technology in recent years, but some results seem so promising, and the approaches used so different from those previously described, that consideration is warranted. Indeed, in many of these publications emphasis is placed on the fact that the problem of trajectory prediction and runway scheduling is complex enough to justify the use of parallel processing and expert systems technologies. The following essentially makes reference to the publications ***"Parallel parametric combinatorial search - Its application to runway scheduling"*** [Ref. 42], ***"Terminal area flight path generation using parallel constraint propagation"*** [Ref. 43] and ***"Expert Systems for the generation of Terminal Area arrival paths for civil transport"*** [Ref. 44].

### An Expert System Approach

A Flight Plan Generator has been designed in the form of an Expert System. It provides a generic means of easily creating sets of landing arrival paths called "**Patterns**", and a simple means of selecting a 4D path from a Pattern, given aircraft performance. The Pattern is the keystone of this representational model of flight path plans. Basically, a Pattern is a predefined type of flight path with degrees of freedom which can be adjusted to form various paths with similar properties. The Expert System also provides an easy method of imposing constraints arising from ATC practice and procedures, ATC separation criteria, controller intervention, etc. on the path selection process. The Expert System assumes that not all possible Patterns are yet known, and that not all future constraints, interventions, etc, have been identified. A "Software System" is provided by the designer so that later "knowledge engineers" can use it to tailor its application to the specific requirements of operation in any particular terminal area or set of circumstances.

A Pattern can be split into segments (turn, deceleration, descent, straight and level path, etc) of which the timing, or the heading, speed and altitude can be selected to produce a particular path belonging to this Pattern. It can thus be associated to a current STAR procedure. The selection process also includes the possible elimination of any segment (a null change). A set of Patterns is called a "Configuration", since it corresponds to any operating configuration of the terminal area airspace. The actual number of Paths in a Pattern is infinite since endless timings or speed, heading and altitude changes can be chosen. A realistic implementation uses intervals of 5 kts for speed changes, 5° for heading changes and 500 ft for altitude changes.

For any aircraft and desired origin-time and destination-time, there are many degrees of freedom in finding a path. An ATC controller can easily impose many further constraints in real time, or he may wish to impose general rules or strategies for path selection, e.g. to declare a nominal offset for the downwind for nominal aircraft, reserving an inner downwind offset for slow aircraft and an outer downwind for

faster aircraft. Even with these additional rules and constraints, there still remain multiple degrees of freedom to define matching constraints and arrival paths. The computer process of selecting these residual parameters in the Expert System consists of an "**ordered search process**" which has priorities for certain "nominal" values of heading, speed, and altitude, and may depend on other factors such as the sequence of landings and takeoffs, or aircraft entry points. The Path Generation process begins with this "nominal" phase.

The use of parallel processing in the generation of flight paths by constraint propagation can ensure that separation standards to avoid conflicts in a multi-aircraft, multi-runway environment could be met along the whole path, including at landing time. The principle used is the following : a constraint is a declarative statement of a relationship between parameters involved in the definition of a flight path pattern. A network of constraints is built as a description of a Pattern, which encompasses the relationship between its various degrees of freedom. Propagation of the effects of the constraints is carried out automatically by an underlying mechanism. Information is propagated through the network in the form of values for the parameters. Deduction is performed locally and the results of the local computations are in turn propagated to contribute to the progressive elaboration of a flight path plan. The consistency of the network of constraints is ensured by detecting any inconsistency in the structure of the flight path plan.

In the process of detecting conflicts between trajectories, most elements of which they are composed at a given level of abstraction are conflict-free. The strategy used for conflict detection consists of recognising quickly and economically that large portions of trajectory are conflict-free. So only a minority of these elements should have to be taken into account for further investigation. This strategy is applied recursively, focusing on the elements which are potential sources of conflicts. The conflict resolution strategy specifies pertinent path parameters depending on the situation as regards these conflicting elements. The Path Generation process returns to continue the ordered search for a conflict-free path.

#### Dynamic Operation of Merge and Final Spacing

If a schedule is created, it must be possible to control aircraft so as to execute the schedule with some degree of accuracy and reliability. This can be done via a "**Path Conformance Monitoring**" function whereby the adherence of aircraft to their pre-planned, assigned paths is monitored. Conformance errors are one source of operational deviations. As each deviation occurs, there is a choice between regaining the planned path, or generating a new path from the current position. Improving the precision of control, especially over the final three segments (i.e. turn to base leg, turn to intercept leg and reduction to final approach speed), is essential to achieving precision in executing the runway schedule, and thereby operating at full capacity rates.

Work is underway on an automated ground control process for "**Final Spacing**" of landing aircraft (*Advanced Cueing of Controllers for Achieving Landing Spacings of Aircraft*), but as a distinctly separate deterministic control process, and not as an Expert System extension. Nevertheless, it could be associated with the Path Generation described above, and the Expert System approach can be extended to handle the rare and sudden large adjustments in retiming and rescheduling runway operation which could still occur in the Merge and Final Spacing Zone. Examples of such unexpected operational events are missed approach, aborted takeoff, airborne emergency, etc. Failure to handle these unexpected events automatically means that human controllers will take over and impose some ad hoc plan which is likely to be inefficient, although safe and simple. Given a manual takeover, there is a problem in restarting the automated scheduling and path generation functions. It is a challenge to impose all the required changes in a few minutes after such events, and many constraints, such as communications capabilities, require to be integrated into such a system, of which such aspects are under study.

#### Use of Real Hardware

The Monsoon dataflow architecture machine currently being constructed at the MIT Laboratory for delivery to Computer Science in 1991, should have 256 processing elements and provide 2 BIPS peak (1 BIPS sustained) computing power. An early prototype of the machine, with a restricted number of processors, was available when these studies were performed. Generating one path with the completed machine would require approximately four micro-seconds. On a computer which would be even four orders of magnitude slower, generating a feasible flight path plan would not require more than a few hundredths of a second. If one second can be allowed for the generation and selection of a feasible conflict-free path, such a speed gives sufficient leeway to generate a reasonable number of paths and detect potential conflicts.

## XII. SYNTHESIS AND CRITICAL REVIEW

Now that we have had an in-depth look at the various systems described, we see that there are many differences amongst them. These differences even appear between operational ones, which provide different kinds of controllers with different types of assistance : MAESTRO provides the GOT controller with assistance in co-ordinating traffic, COMPAS advises executive controllers how sequence arrivals, and ASA integrates scheduled landing times of inbound aircraft into the complexity of the overall traffic.

Clearly, this indicates that we have to review a number of aspects of these systems, identify which are common and pinpoint the problems encountered and possible solutions proposed by research projects. Differences also need to be identified, and tentative justifications and impacts of choices assessed, in order to show the benefits or the disadvantages of particular approaches.

## 1. LANDING TIME PREDICTION

Basically, this function provides as output "Estimated Times of Arrival" at the runway for each aircraft, which are then passed to the sequencing algorithm. Clearly, all the systems need an on-line trajectory prediction function, which can be provided by an ATC "extended" flight plan processing system, as in the case of MAESTRO, or directly integrated into the automation tool, as in COMPAS or ASA. Two different methods are used by these latter systems, viz:

- Point-mass equations of motion using an energy-state balance and numerical integration algorithm to build successive flight phases (CTAS, TIMER, etc), that we would refer to as a tabular model;
- Parametric equations which approximate to the aircraft's behaviour (generally based on its vertical speed) during the flight phases (ASA, COMPAS, ZOC, TCSDG, etc), that we would refer to as a parametric model.

With respect to the results of the various experiments performed for the validation of these approaches, we see that they both provide information with an acceptable level of accuracy, and only minor details could be improved. It is generally accepted that the other sources of uncertainty (variation in atmospheric conditions, in how different ATC controllers provide clearances, in how different crews fly an aircraft and so on), have a degree of importance many times greater than deviations caused by the resolution of the equations used by the respective models. This does not mean that no further effort needs to be devoted to that topic, since there may arise a possible need for accurate estimates of fuel consumption for instance, or else new aircraft types introduced for which these systems must have an adequate model. This may require detailed information from aircraft manufacturers, which is not always easy to come by.

Generally speaking, the tabular model is computationally heavier, but provides more accurate results if based on precise data, plus a program structure which is more modular (e.g. the aircraft model and the phase description are separated) and more flexible. As an example, let us take the descent phase : the parametric algorithm generally assumes an idle thrust descent and integrates this assumption into the equation describing this phase. The tabular model may use the same assumption, and assign the thrust setting to idle to describe the same flight phase, but it is ready to provide information on a descent phase with another thrust setting, without having to modify its model.

Nevertheless, it may also be argued that very complex models may contain needless variables, because no information is available to specify them, or operational practices completely overrule them. In addition, the precision required could be much more important for specific manoeuvres (the same speed variation has a different impact at cruise level and on the glideslope) and the influence of parameters could be flight-phase dependent (e.g. the bank angle in the final turns, impact of wind on a turn). However, this can be included in another piece of logic (trajectory control function) and only statistical analysis of actual results from experience may prove the overall efficiency of such trajectory prediction algorithms.

## 2. SEQUENCING AND SCHEDULING METHODS

The purpose of sequencing and scheduling methods is to automatically plan the most efficient landing order and to optimally assign spaced landing times to all arrivals. This

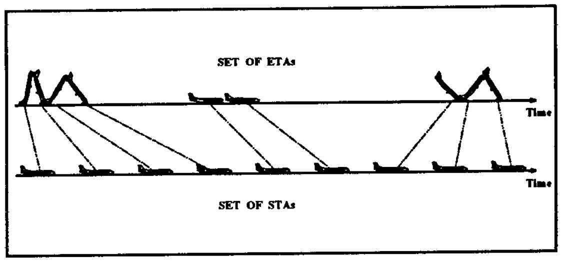


**Figure 27 : Result of the Sequencing process**

can be done using different criteria and scenarios, e.g. minimum speed profile, minimum cost, minimum transit time (time to cross the controlled area). Those criteria used may also be time dependant, functions of the actual circumstances. For instance, provided that the traffic does not exceed the capacity, a philosophy of minimum cost for individual aircraft can be adopted, but during a peak period, this can be changed for a minimum transit time for the earlier aircraft in the peak, and a minimum speed profile for those which are later. Various studies concerning the cost-flight time relationship have been carried out [Ref. 47], showing that the excess cost (actual rather than ideal) of flights can be reduced in order to achieve the lowest cost solution to handle traffic during a specific time interval. However, in the case of data processing systems, some care needs to be taken in constructing a landing time allocation procedure, in terms of fairness, safety and capacity. Indeed, if a computer program is unsafe (i.e. the assumptions on which it bases its processing may give rise to dangerous situations), or reduces the system capacity under given circumstances, then it will be systematically unsafe, or inefficient when such circumstances occur.

### 2.1 Fairness

The scheduling algorithm has to be equally fair to all classes of air traffic and not impose on any one class delays which on average are greater than those imposed on other classes of traffic. Classes of traffic mean not only a distinction between weight categories, but any criteria allowing traffic to be grouped, such as common entry point into the area, flight level, speed or airline. Systems using a "frozen sequence" (ASA, COMPAS, TCSDG, TIMER, CTAS, TATCA) are therefore obliged to use the concept of "**Scheduling windows**" (Figure 28), where all possible aircraft eligible for a given time of arrival are already known by the system when the corresponding landing slot is allocated by the scheduling

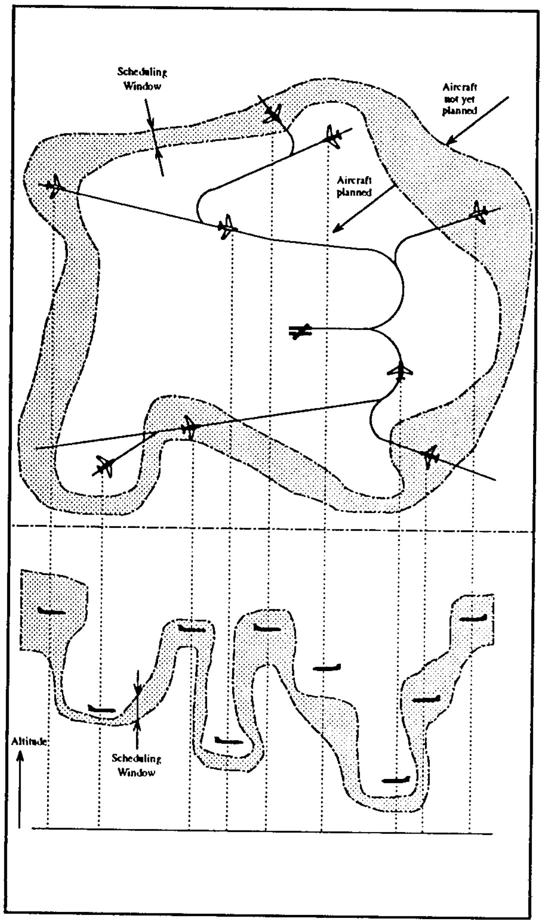


**Figure 28 : Scheduling Window**

algorithm. The research teams using this philosophy propose values determining this window (limits, duration) which are experimental or justified by a theoretical approach. They agree to start the sequencing algorithm before the Top-Of-Descent (≈ 30-40 min before touchdown), in order to take advantage of speed control at cruise level, and an automatic resequencing on entry in the merging and final spacing area (CTAS) seems appropriate (≈ 10 min before touchdown). The sequence is frozen when aircraft are still in the sector areas, which means that they are handled by different controller teams. This also means that if an executive controller is not behaving in line with the sequence, all the advisories he receives from the system will be invalid until he manually changes the computer suggested sequence. This shows the value of having at least one automatic resequencing, in order to avoid situations where one controller who does not follow the proposed plan and does not tell the system what he wants to do, makes all the advisories produced unreliable for everybody. In addition, if there is a significant delay before the sequence number allocation, a slow aircraft not yet planned could be followed by a fast one, planned already. Some systems are dealing with this by looking ahead of the scheduling horizon to perform a preliminary "unfreeze" sequence.

Obviously, a system such as ZOC, which allows dynamic resequencing, does not have to handle those aspects, but on the other hand it has to ensure some sequence stability and to use a valid set of criteria to decide when resequencing has to occur.

A feature common to nearly all the systems is the possibility for the controller to overrule the proposed sequence. Again this can generate a complex problem when a resequencing request triggers a new sequence generation using the controller-imposed constraint. Indeed, the scheduler is in essence a real-time algorithm that transforms sequences of estimated times of arrival (ETAs) into reordered sequences of scheduled times of arrival (STAs) using one or more scheduling protocols. Operation in real time implies that the algorithm generates the STAs in a small fraction of the time it takes each aircraft to fly from its initial position to touchdown. This condition, combined with those additional operational constraints, places significant computational constraints on the algorithm. Nevertheless surprising solutions may arise when efforts are made to simplify this dynamic problem too much. MAESTRO for instance, bases its sequencing on runway arrival times, which are in fact deduced from control area entry point conditions. Its resequencing process will thus not take into account the current state of a particular aircraft, i.e. its adherence to the plan, a delay already observed, etc, to produce the new sequence. Under such circumstances, efforts are effectively being made to adapt a computer-generated plan to the actual traffic pattern, while the system responding to that request does not take into account the given actual situation, but refers rather to past conditions, an arrangement that could generate strange suggestions.

### 2.2 Safety

In terms of safety, the basic requirement is, very obviously, that landing separation criteria are not violated. Minimum separation matrices, expressed as distances in nautical miles, are commonly used. Because the sequencing algorithm is time-based, the matrix has to be converted into time, which is not always straightforward because of the influence of the wind and the final approach speed. For example, under headwind conditions, when the trailing aircraft flies at constant airspeed independent of the wind, its ground speed is reduced by the speed of the wind. Thus for a specific separation in miles, a time-separation matrix will in this case, require larger separations. Because of the influence of the True Air Speed on the different parameters describing aircraft motion, this time-separation variation does not correspond to a global shift for every aircraft category. This indicates that systems like COMPAS which use a fixed time-separation matrix (see Table 2 - chapter II) may base their processing on a less than optimum (and safe) actual situation. This seems to be compensated in operation by the imposition of lower flow rate by the executive controller when such situations arise. Other systems, like MAESTRO, which does not seem to handle such parameters, uses both flow rate and "pressure at the runway" to allow the control team some flexibility regarding the plan. Both system turnarounds, even if finally

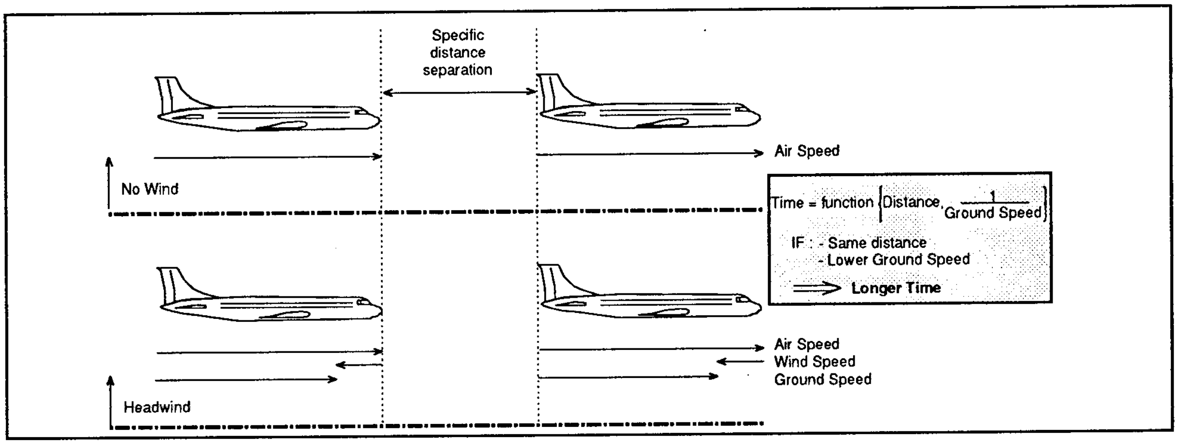


**Figure 29 : Wind influence on separation requirements**

providing a safe environment, obviously have a negative effect on system capacity, which will be discussed later. Another point in connection with sequencing which also relates to security, is that care must also be taken as far as possible where sequence-induced conflicts are concerned. This can be illustrated by a situation where two identical aircraft, enter the control area with the same cruise speed (IAS), and the same destination runway, but with an altitude separation of, say 2.000 ft.: because of the influence of altitude in the translation from IAS to True Air Speed (TAS), the higher aircraft will have an estimated time of arrival earlier than the lower, and will be inserted before the lower into the landing sequence, according to simple FCFS. Very obviously, it will thus generate a short-term conflict. Such operational constraints can be directly checked by the sequencing algorithm, without making use of a separate conflict-detection module.

### 2.3 Capacity

ATC separation criteria applied both at the merge area, where final approach spacing is established, and at the runway, between landing and take-off operations, cause an upper limit or "capacity" to be placed upon average traffic flow rates. A distinction can be made between landing flow capacity, takeoff flow capacity, mixed runway operations flow capacity and corridor capacity. These capacities are expressed in average operations per hour, and will vary up and down in any given hour according to the separations which must be applied to the actual mix and sequence of types of aircraft in that particular hour's traffic flow. In order to prevent congestion or "starvation" in terminal area airspace, the landing flows may be metered to control the number of aircraft simultaneously present in any sector of terminal airspace. In fact, it is possible to identify three types of throughput gain that can be achieved through the proposed automation tools: two relate directly to the sequencing, and the third one, relating to profile control advisories, will be discussed later. As already stated, the first gain is achieved by smoothing and derandomising the arrival streams converging on the terminal area. Indeed the metering rate between en-route and terminal airspace is currently set by manual input of an airport acceptance rate. Typically this rate remains fixed for long periods of time during which the average achievable throughput may fluctuate because of changing winds, changing mixes of light and heavy aircraft, changing ratios of arrivals and departures, etc. By the time control personnel note and react to a problem with the metering rate, capacity may already be lost. Furthermore, the metering may not respond efficiently to transient throughput variations caused by runway configuration changes, missed approaches, emergencies, etc. A common goal of the proposed systems is to allow a dynamic delivery rate so that airport capacity is fully utilised without producing congestion or excessive gaps within the terminal airspace.

The second increase in throughput is achieved by using landing sequences that reduce the need for additional wake-vortex separation. The preceding chapters show that both aspects are covered by different ordering rules. Basically, most of the systems apply First-Come-First-Served at the runway ordering. The reasons are simple:

- FCFS reflects an indisputable sense of justice to the users;
- Optimal reordering of complex problems (integration of takeoffs, overflights and landings over an extended control area and a large timescale) is a tough combinatorial problem for computers, let alone human operators, to solve.

One technique to improve FCFS is known as "**negative delay**" or "**time advance**", referring to the advantage a system can take of filling the "gaps" which precede peak periods. TCSDG, CTAS and ZOC, for instance, allow the first aircraft of a group to be speeded up to arrive sooner than its nominal ETA, and all the following aircraft will then have their delays decreased by the same amount of time. In these systems, such a procedure occurs only when at least one of the immediately-following aircraft would otherwise be delayed. CTAS at present uses a maximum time advance of 1 min for all aircraft, but is looking at a system using a fraction of the available time-advance of the leading aircraft.

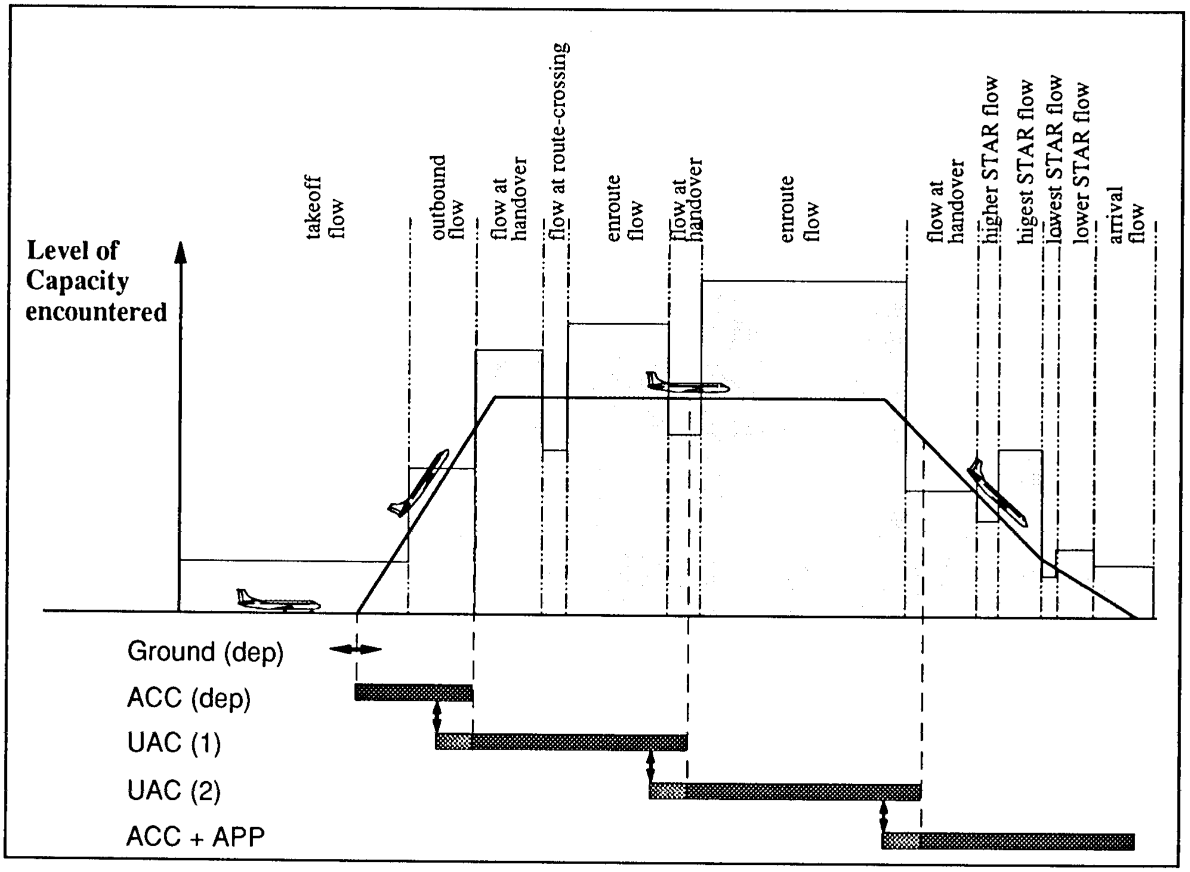


**Figure 30 : Sample of Capacity variation**

ZOC now asks an aircraft to achieve its earliest landing time if accelerated. Another method, modifying the FCFS order, which takes advantage of the difference in separation requirement between aircraft weight categories (e.g. the elapsed time of the sequence *heavy-heavy-large* is different from a *heavy-large-heavy*), is referred to as the "**Position Shift**" method. Case studies show that the average number of shifts in the optimal schedule does not exceed two, and half times the amount these shifts are already ahead. Runway capacity may be almost double that of FCFS and delays can be reduced by up to 90 percent [Ref. 42] Research is now in hand with a view to the ZOC system using a combined "Weight category - average speed profile on the common path (after localiser interception)" criterion as the basis for its position shift algorithm.

Systems like COMPAS mix both optimisation processes, using a branch-and-bound technique with a global "cost" function (total delay time) to determine which aircraft to delay or to expedite, according to a possible position shift.

## 3. FLIGHT CONTROL - CONFLICT-FREE PATH

As pointed out under the landing time prediction topic, in order to provide Estimated Time of Arrival, most of the systems generate an "extended flight plan" based on a succession of flight phases which completely describe the flight in terms of vertical, horizontal and speed profiles. This shows that we have in fact three different processing phases when providing a 4D profile matching the constraints which an arriving stream of flight has to match:

- a landing time prediction based on the extended flight plan;
- a extended flight plan "maintenance" processing phase which determines the optimum profile from the actual constraints and the numerous degrees of freedom still available, and
- an information display system providing the control team with the proposed assistance.

The maintenance process allows, for example, providing the sequencer with basic control range boundaries (e.g. earliest and latest possible landing time : COMPAS, MAESTRO, ZOC, TCSDG, etc), but also criteria for efficient flight control: delay assessment for MAESTRO (Fig 9 - chapter III), ZOC profile manager, CTAS aircraft selection method (Inquiry Mode), etc. The information display system thus generates advisories which are dependant on the phase of flight. If we look again to the MAESTRO delay assessment figure, an advisory for spending more time in the en-route part for global delay absorption will essentially affect the

flight in terms of cruise and descent speeds. After TMA hand-over clearances, these control variables obviously become obsolete, and only precise control for approach speed reduction and final turns are still valid. It is the combination of these three modules (prediction, maintenance, display) which allows the final increase in throughput by increased precision in the final spacing process, thus allowing spacing buffers between successive arrivals to be reduced. But it is naturally the flight maintenance module which synchronises these control procedures in order to allow any benefit gained, e.g. in the "fine-tuning" of an aircraft in the TMA, to be shared out among the overall traffic surrounding the TMA.

Nevertheless, a distinction can be made when speaking about flight control logic. Indeed, advisories can be provided for two different goals, viz:

- how to stay on, or return to the scheduled plan;
- how to efficiently achieve the new plan, based on the current situation.

This distinction will be explained in more detail in section 4 (see below), but we can already see a direct impact on one of the system features, which is the "conflict-free path" concept. Essentially, for each of the systems described, this refers to the latest part of the flight (i.e. the segment flown on the localiser), which is common for all the inbound aircraft. This "automatic conflict detection and resolution" feature results from the operation of the sequencer component which spaces the aircraft on the runway according to a "minimum separation matrix" (with the restriction already discussed for the time separation matrix used by some systems). Publications [Ref. 45,46] have shown that using speed control procedures to achieve such proposed sequences already provides an average reduction of 60% of the potential conflicts. Unfortunately the remaining conflicts concentrate around the route convergence points, in particular the approach fixes (or feeder gates). CTAS has proved that a conflict detection module and resulting warnings based on predicted trajectories is very feasible, whereas a system which provides control advisories based on observed deviations from the predicted trajectories cannot generate conflict warning based on the actual traffic situation. This is only applicable to CTAS "selected aircraft" and ZOC profile manager, which both update flight plans. On the other hand, a suitable balance between potential conflict detection and false alarm generation must be found for the "look ahead situation".

## 4. SYSTEM-CONTROLLER RELATIONSHIP

All the systems described provide the control team with a "computer-generated plan". Speaking in terms of System-Controller relationship, a distinction can be made between systems, on the basis of Plan Conformance Monitoring and the manner in which corresponding amendments are performed, viz:

- mainly by controllers (COMPAS, MAESTRO, TCSDG, ASA, etc);
- mainly by the system (ZOC).

And for both types, differences can also be seen in terms of:

- possible controller actions (e.g. sequence modification);
- assistance provided to achieve the requested actions (e.g. new speed profiles to achieve the new sequence).

Indeed, systems like MAESTRO and COMPAS allow the control team to specify a new sequence, but do not provide the executive controller with suggested speed, heading, etc, to achieve it. CTAS is rather more special, because even if following the first trend, it nevertheless allows a dynamic resequencing when entering the TMA. It will thus be considered as a hybrid system, which provides, for this system category, the control team with the most sophisticated assistance to achieve the requested plan (Horizontal guidance, etc). It seems that systems following the first trend, are much more likely to encounter the problem of "*... there will be cases when the landing sequence numbers and speeds which the computer advises will not be achievable.*" [Ref. 16], and so force the control team to modify the computer-generated plan, if they want to make the advisories consistent with the current situation. This means that the controller not only "**stays in the control loop**", but also must "**not leave the computer alone**".

The only way to solve this problem is to provide the controller with powerful and convenient assistance, like CTAS does. Indeed, efficient solutions, provided by detailed and complex algorithms, are presented, when possible, into a graphical format that enhances rapid perception of advisory information. This interface also makes extensive use of on-screen switches and menus selectable by manipulating a mouse or a trackerball, using the latest evolutions of powerful engineering workstation technology. This allows the executive controller to interface with the system, and even request "heavy" constraints on it, in a very simple way (e.g. Inquiry Mode), and receive precise information to achieve his goals (e.g. Horizontal Guidance). However, it must be remembered that, even if these powerful tools lighten this kind of man-machine transactions, these transactions are still required.

On the other hand, the other type of system (illustrated by the ZOC system), has to find a good compromise between an optimum solution for the actual traffic situation at each processing step, and conservation requirements which cause it to deviate it from this optimum. This is where some controller inputs, or datalink information may provide a high gain for the system. Imagine for instance a controller clearing an aircraft off-route to a given beacon. The elapsed time required for the system to detect the flight plan modification, and implement it into its flight prediction, could already be used to advantage for the rest of the traffic if it was, e.g. entered by the controller when issuing the clearance.

This also clearly indicates a difference in perception of the advisories generated (*please follow them*, or *please try to do better than*); indeed, to build the flight plan, the systems require information on procedures (STARs, SIDs, airlines operating rules, etc). This means that the data processing system has to provide "plans" based on average pilot, average controller. Operational practices clearly show that under

given circumstances, agreement can be found between controller and pilot to achieve better performances (direct routing, shortcut, etc). Obviously, the automated tool must certainly allow this kind of action (without penalty, e.g. on the controller workload), but also allow the rest of the traffic to take advantage of the benefit gained by the aircraft concerned.

Imagine for instance an aircraft already in the TMA, and flying on its downwind leg. The data processing system is ready to provide the controller with an advisory indicating the turn to base, but because of operational reasons (downwind leg closer to the runway axe, aircraft lower than schedule, etc), the controller decides to turn it earlier than advised. If the system (as ZOC does) can detect this, a new landing time, according to the current situation, will be given to this aircraft, which will thus modify the constraints for the rest of the traffic, perhaps reducing some other flight delays.

## XIII. CONCLUSIONS

Some results of research work which has been carried out around the world in the last 25 years to face the challenge of designing efficient automated tools for Air Traffic Management systems, have been presented in the previous chapters. Because the ultimate aims of all these projects are identical, the major system components have a strong resemblance to each other. These components have been analysed and discussed in the previous chapter (Synthesis and Critical Review). They all concentrate on ground-based management of inbound traffic in a control zone which covers 100-300 nm around one or more main terminals. All processing is basically performed on a set of ETAs, provided by the ATC host system, or by the tool itself. For the latter, an "extended flight plan" is built for every aircraft, and according to the system, "parametric" or "tabular" resolution of the equations of motion are solved, in order to provide an ETA corresponding to each flight. As far as pure "constrained time of arrival" is concerned, validation experiments have shown that the inherent sources of uncertainty have a degree of importance many times greater than deviations caused by the resolution of the equations used by respective models, which provide information with an acceptable level of accuracy.

This sequence of ETAs is afterwards transformed into a reordered sequence of STAs, in order to assign optimally spaced landing times to all arrivals. Again, according to the system, this can be performed in various ways, as a function of the scheduling algorithm used, and all the previously discussed constraints (separation matrix, minimum cost flight, minimum transit time, sequence-induced conflict, etc). Various aspects of this sequencing mechanism have been reviewed, in terms of fairness, safety and capacity. Distinction has been made between systems which build a "frozen sequence", and others which perform a "dynamic resequencing". Apparently the latter sort of system avoids encountering numerous problems for which, in the other ones, controller actions are required (manual sequence update for route shortcut handling, missed approach, etc). This point seems to be most important e.g. to permanently provide the overall control team (i.e. ACC, APP and TWR) with a consistent proposal for the actual traffic situation. As it was shown by the MAESTRO limitations in terms of resequencing, the problem of sequencing is dynamic in essence. The COMPAS system, for its part, even if using a sophisticated Branch-and-Bound optimisation technique, seems to be able to recommend conflict-provoking situations on the localiser, again caused by a weak consideration of the actual flight conditions.

However, the reasons for those limitations can easily be understood: the sequencer algorithm may actually become computationally very heavy if it really has to consider the permanently changing environment, illustrated for example by variable ETAs. For the systems using "frozen sequence", only CTAS seems to have succeeded in implementing sophisticated algorithms (Time Advance, Position Shift) to handle such problems, in conjunction with this dynamic environment ("selected aircraft").

Another distinction has been made in terms of "Plan Conformance Monitoring", according to the global system philosophy: achieving at all costs a plan, determined at a given moment to be the "optimal one", or on the other hand, permanently checking against traffic evolution to ensure "optimal solution of the actual situation". The information display system may thus provide two different kind of advisories: how to maintain the scheduled plan, or how to implement the latest one. Those advisories are generated by the "4D profile manager" module, using adequate control variables which are flight phase dependant. Nevertheless, two separate levels of advisories can be generated:

- slot time and Estimated Time Over (ETOs) beacons or Reporting Point for ASA, or Reduce and eXpedite for COMPAS, or the initial delay to be absorbed for MAESTRO;
- speed, heading, countdown for turn commencement, as proposed by CTAS, TIMER, TATCA, ZOC, PACTAS.

This distinction, combined with the previous one, has a direct impact on the System-Controller relationship, since the amendments corresponding to the Plan Conformance Monitor may be performed mainly by the controller, or mainly by the system itself, with corresponding assistance provided by the system to achieve these amendments. It indicates that systems which prevent the controller from "leaving the computer alone" are therefore necessary, in order to maintain synchronisation between such systems and the current situation, to provide powerful and convenient assistance, like CTAS does. The assistance itself can thus be envisaged in two different ways, viz: a request for an as-close-as-possible implementation of the suggested advisories, or an invitation to do at least as well as the advisory suggested (assuming a system highly dynamic, like ZOC proposes). The latter clearly shows that **opportunities exist to efficiently integrate controller skills into a more automated environment, taking advantages of both kind of resources (man & machine), without putting penalty or restriction on the controller.**

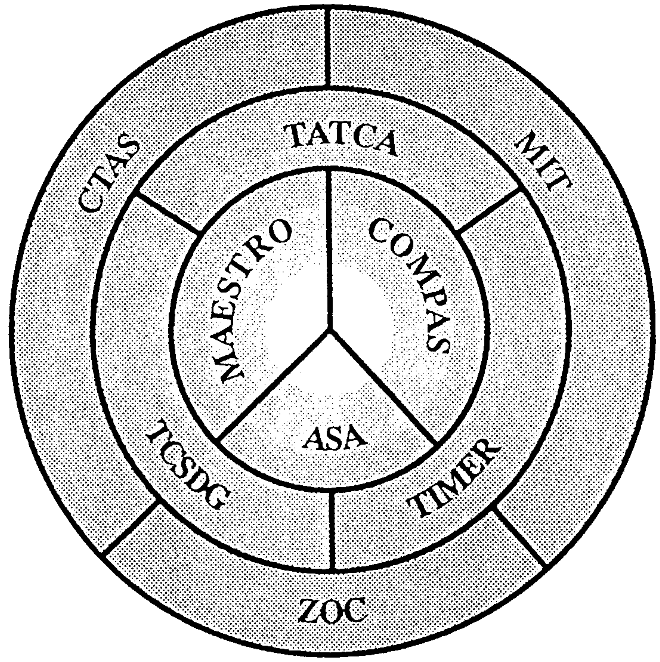


**Figure 31 : levels of system functionality**

The various distinctions drawn above can be illustrated by Figure 31, where the three operational tools were regrouped (ASA, COMPAS, MAESTRO), providing a "kernel" of automated tools for which one of the greatest merits is to be part of an already operational environment.On the opposite border, we find CTAS, ZOC and the MIT work, showing three different philosophies of integrating the complexity of the terminal area problem within the overall ATC environment. Each of these systems can be considered as a leader of their respective type, as shown by the discussion in the preceding chapter: level of complexity reached for landing time prediction, sequencing, scheduling, flight control, system-controller relationship, etc.

The intermediate level shows the research work that proposes the same kind of automation as CTAS, but at a lower level of complexity, or focusing more on specific aspects of the overall problem (e.g. influence of parameters for the scheduling windows).

As a final word, we can hope that a consensus on the challenge of designing such Air Traffic Management systems can be found by the various organisations concerned, and especially by the international administrations, in order to allow the civil aviation community to profit by services they can expect from modern, but already existing technology.

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## XV. ABBREVIATIONS

| | |
|---|---|
| *AAA* | *Amsterdam Advanced Air Traffic Control System* |
| *ACC* | *Area Control Centre* |
| *ACCESS* | *Aircraft Control Console for Experiments and Simulation Studies* |
| *APP* | *APProach* |
| *ARTS* | *Automated Radar Terminal System* |
| *ASA* | *Automatic Slot Assignment* |
| *ATC* | *Air Traffic Control* |
| *BFS* | *Bundesanstalt für Flugsicherung (German ATC authorities)* |
| *CAS* | *Calibrated Air Speed* |
| *CAUTRA* | *Coordonnateur AUtomatique du TRafic Aérien (French ATC System)* |
| *CDT* | *Command Delivery Time* |
| *CENA* | *Centre d'Etudes de la Navigation Aérienne (French Aeronautical Research Establishment)* |
| *CINTIA* | *Control of INbound Trajectories for Individual Aircraft* |
| *CLR* | *Cleared* |
| *COMPAS* | *Computer Oriented Metering Planning and Advisory System* |
| *CTAS* | *Center/Tracon Automation System* |
| *CTR* | *Control Terminal Region* |
| *D* | *Delay* |
| *DA* | *Descent Advisor* |
| *Dc* | *Delay to be absorbed within ACC* |
| *DERD-MC* | *Display of Extracted Radar Data - Microcomputer-Controlled* |
| *DICE* | *Direct-course error* |
| *DLR* | *Deutsche Forschungsanstalt für Luft- und Raumfahrt (German Aerospace Research Establishment)* |
| *DME* | *Distance Measuring Equipment* |
| *Dp* | *Delay to be absorbed within APP* |
| *DPT* | *Dynamic Time-based Planning* |
| *EARTS* | *En route Automated Radar Tracking System* |
| *EAT* | *Expected Approach Time* |
| *ECAC* | *European Civil Aviation Conference* |
| *EDD* | *Electronic Data Display* |
| *EETOGT* | *Earliest Estimated Time Over GaTe* |
| *EFPD* | *Extended Flight Plan Description* |
| *EROCOA* | *Equivalent Rate Of Change Of Altitude* |
| *ESL* | *Entry Sequence List* |
| *ETA* | *Estimated Time of Arrival* |
| *ETOGT* | *Estimated Time Over GaTe* |
| *EUROCONTROL* | *European Organisation for Safety of Air Navigation* |
| *FAA* | *Federal Aviation Administration* |
| *FAST* | *Final Approach Spacing Tool* |
| *FATA* | *Final Approach Timing Aid* |
| *FCFS* | *First-Come-First-Served* |
| *FDPS* | *Flight Data Processing System* |
| *FL* | *Flight Level* |
| *FPUD* | *Flight Progress Updating Device* |
| *GOT* | *Gestion Optimisée du Trafic (Optimised Traffic Management)* |
| *HASM* | *Heure d'Arrivée Séquencée de MAESTRO (Sequenced arrival time at the runway)* |
| *HEBC* | *Heure Estimée Balise d'attente du Calculateur (Estimated Time at the TMA entry point)* |
| *HETM* | *Heure Estimée d'Atterrissage de MAESTRO (Estimated arrival time at the runway)* |
| *HSI* | *Human-System Interface* |
| *I* | *Inquiry mode* |
| *IAS* | *Indicated Air Speed* |
| *ICAO* | *International Civil Aviation Organisation* |
| *IFR* | *Instrument Flight Rules* |
| *ILS* | *Instrument Landing System* |
| *IMC* | *Instrument Meteorological Conditions* |
| *KT* | *Knots* |
| *LAN* | *Local Area Network* |
| *LAS* | *Last Assigned landing Slot* |
| *LIV* | *Landing InterVal* |
| *LOC* | *Landing Order Calculator* |
| *MADAP* | *Maastricht Automatic DAta Processing (and display system)* |
| *MAESTRO* | *Means to Aid Expedition and Sequencing of Traffic with Research of Optimization* |
| *MET* | *METeorological* |
| *MIT* | *Massachussets Institute of Technology* |
| *MLS* | *Microwave Landing System* |
| *MMI* | *Man-Machine Interface* |
| *MOTAS* | *Mission Oriented Terminal Area Simulation* |
| *NASA* | *National Aeronautics and Space Administration* |
| *NM* | *Nautical Mile* |
| *p* | *pression à la piste (MAESTRO pressure at the runway)* |
| *PACTAS* | *Predictive Approach Control Tactical Advisory System* |
| *PARZOC* | *PARabolic approximation of aircraft performance for use in a Zone of Convergence* |
| *PVD* | *Plan View Display* |
| *RETD* | *Revised Estimated Time of Departure* |
| *RI* | *Route Intercept* |
| *RLD* | *RijksLuchtvaartDienst (Netherlands Department of Civil Aviation)* |
| *ROSAS* | *Regional Organisation of the Sequencing* |

| | |
|---|---|
| | *and Scheduling of Aircraft System* |
| *RP* | *Reporting Point* |
| *RSRE* | *Royal Signals and Radar Establishment* |
| *R/T* | *Radio-Telecommunication* |
| *SARP* | *Signaal Automated Radar Processing (Dutch ATC System)* |
| *SCA* | *Speed Control Adviser* |
| *SID* | *Standard Instrument Departure* |
| *SLT* | *Scheduled Landing Time* |
| *SP* | *Standard Procedure profile* |
| *STA* | *Scheduled Time of Arrival* |
| *STANS* | *Simulation facility for a Total Air Navigation System* |
| *STAR* | *STandard instrument Arrival Route* |
| *STPV* | *Service du Traitement des Plans de Vols (French Flight Plan Processing Service)* |
| *STR* | *Service du Traitement des données Radar (French Radar data Processing Service)* |
| *TAAS* | *Terminal Advanced Automation System* |
| *TAATM* | *Terminal Area Air Traffic Model* |
| *TAF* | *Terminal Approach Fix* |
| *TAS* | *True Air Speed* |
| *TAT* | *Terminal Approach Time* |
| *TATCA* | *Terminal Air Traffic Control Automation project* |
| *TATM* | *Terminal Air Traffic Management* |
| *TCSDG* | *Terminal Control Systems Development Group* |
| *TIMER* | *Traffic Intelligence for the Management of Efficient Runway-scheduling* |
| *TMA* | *Terminal Manoeuvring Area* |
| | *Traffic Management Advisor* |
| *TOD* | *Top-Of-Descent* |
| *TWR* | *Tower* |
| *U.S.* | *United States of America* |
| *VFR* | *Visual Flight Rules* |
| *VOR* | *VHF Omnidirectional Radio range* |
| *WC* | *Waypoint Capture* |
| *ZKSD* | *Zentraler Kontrollstreifendruck (German central flight strip printing unit)* |
| *ZOC* | *Zone Of Convergence* |
| *4-D* | *Four dimensional (latitude, longitude, altitude and time)* |

## ADDENDUM: STATUS OF THE US SYSTEM AS OF JUNE 1992

CTAS has been implemented at Denver (Colorado) since September 1991; it is not operational, it is still in a test period; it covers an area which corresponds roughly to 45 mn of flight before arrival; it manages the traffic to secondary airports around Denver too, it takes into account the transit traffic.

It is recalled that all synthetic plots collected by all radars in the USA are sent to the National Flow Control Facility, located in Washington. Data are refreshed every 5 mn. The 23 control centres in the States have access to these files. This is the ATMS (Advanced Traffic Management System). The Denver Control may know the landing sequences within the next 1 or 2 hours with an accuracy of 1 to 5 mn for the planes which are already in flight (ASD: Air Situation Display). However, at this level conflicts are not detected.

Every day at 06.00 am a team of meteo and flight safety specialists meet and decide about the traffic restrictions - if any - for the current day; landing rates may be estimated at that time for the day. The Denver area is perturbed by meteo phenoomena very often mainly during summer and autumn; active storms, convexion zone, clear air turbulance, downbursts, ...

In the USA most airports are multirunways (presently, they are 4 runways in Denver - but two new runways are to be built soon - there will be 10 runways at Houston soon) and the landing rate capacity is not the dominant limiting factor like it is in Europe where most airports have no more than 2 runways in operation at a time. Table I gives the specifications for parallel runways operated independently. The traffic management around the airport is of prime importance for achieving the expected maximum landing time. The present Denver situation is summarized in figure 32 when terminal area of arrival are updated continously, it is then estimated that the margin error is much less an 1 mn; this is normally 10 to 20 s. From E1....E4 the flight management is controlled by another system called "FAST" which operated over 20 to 30 mn before the touch down.

| Parallel runways | |
|---|---|
| <u>ICAO Specifications for IFR flights</u> | |
| fully independant runways | 1525 m |
| simultaneous approaches accepted if distance between planes stays greater than 3.7 km | 760 m |
| <u>ECAC proposal</u> | |
| if airport equipped with radar refreshing data every 2.4 s | 1035 m |

**Table I**

In the computer, the hierarchy of modification of flight parameters is, by order of priority :

(1) to modify the "top of descent"

(2) to modify the velocity of the plane which is the first one in the sequence concerned

(3) to modify Z by 4000 ft without modifying IAS

(4) to modify Z by 4000 ft and to modify IAS

(5) to modify the route.

(It is surprising that no discrimination is attached to the size of the aircraft, even in the re-sequencing process - this will be corrected soon...).

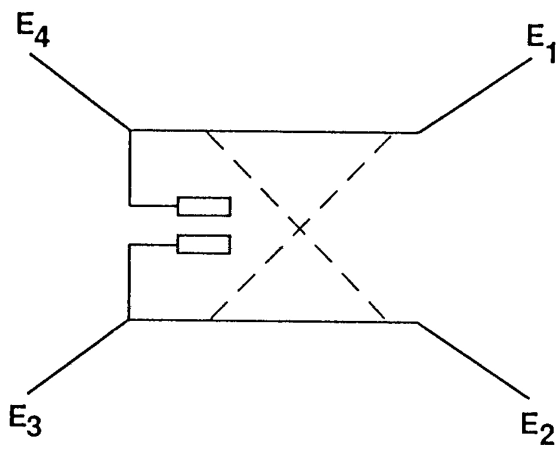


Figure 32

R-NAV can be used before the Entry points or Feeder points E1...E4 but not after that point up to the runways.

C-TAS manages the conflicts (this is a difference with MAESTRO or COMPAS).

In order to optimize both the conflicts and sequencing on the entry points a criterion is used: it is a mixture of "delays", "fuel", "exchange of plane inside a sequence", "delay with regard to the original time of arrival". Some of these components intervene also as a quadratic component. This is the "Cost Index" which comes from and generalizes the "company rules". They show that accuracy of 30 may be reached for the whole traffic at the "feeder points" which allows a good initialisation for FAST.

# CHAPTER 6

## DECISION MAKING AIDS

# DESIGN OF DECISION MAKING AIDS for ATC SYSTEMS

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**ABSTRACT**

The traffic capacity of an Air Traffic Control sector is often limited by the available throughput of the air-ground communication channel and/or the limitations of the human controller team. The next generation of ATC systems, covered by the EATCHIP Phase III Workprogramme, aims to, inter alia, increase sector capacity by improving air-ground and ground-ground communication capabilities and introducing "task sharing" between humans and machines. The thus "extended controller team" constitutes an optimum symbiosis between human and machine capabilities.

An operational concept has been developed to achieve the user requirements. It is essential that efficient "resource management" is introduced to optimise the performance of the extended controller team to define at any time: *"Who* (humans or machines) does *what*, *when* and *how"*. Consequently the automated functions cannot be designed in isolation, but must be developed as a consistent suite of tools supporting each other's functionality. Moreover, as in the aircraft cockpit, task sharing between humans and machines will have an impact on controller training and preparation for contingencies.

Trajectory prediction and conflict risk analysis are the technical prerequisites for Decision Making Aids. Different methodologies are analysed in terms of required infrastructure, ATC efficiency and impact on flight operating costs. Their impact on working rules and procedures is discussed.

## 1. INTRODUCTION

In today's Air Traffic Control (ATC) environment the controller is often one of the limiting factors in the control loop. The number of flights he or she can handle efficiently is limited by the physical and mental workload characteristics of the human being. However, ultimately, only the human, not technology, can cope with the unpredictable. Therefore the starting point for the development of automated system support is the assumption that the *controller decides and the system supports*. To that effect assistance must be provided through the appropriate application of automated help in the three following domains: *Human-Machine Interface* (HMI), *system supported Co-ordination And Transfer* (CAT) and *Decision Making Aids* (DMAs). Together they constitute the backbone of the operational concept developed for the *European Air Traffic Control Harmonisation and Implementation Programme* (EATCHIP) Phase III Work Programme (Reference 1). This defines the European Air Traffic Management (ATM) system until the turn of the century. The fulfilment of this operational concept will permit an increase in the number of flights handled per control team (i.e. per volume of airspace) or, in other words, the average workload of the human per aircraft handled will be reduced.

The decision making process of the controller is based essentially on the prediction of the medium-term future. If the predicted future seems unsatisfactory then remedial action is undertaken in order that safety is assured and that the overall ATC system efficiency can be optimised. The purpose of decision making aids is to provide the controller with better support for making decisions (Reference 2).

From the point of view of system engineering it is very tempting to start the design of the next generation of ATM systems by following a top-down approach. However due to the complexity of the system, an evolutionary approach is required rather than a revolutionary one. Nevertheless, to be practical, shorter term solutions to specific problems must be designed

with a longer term system philosophy in mind. This paper addresses the different aspects to be considered for the design of automated support functions for the air traffic controller, in particular the decision making aids.

## 2. THE ATC CONTEXT

The starting point for the development of automated system support is the assumption that the *controller decides and the system supports*. Further, it is assumed that, in the time frame envisaged, the airspace structure will not be considerably different from the one in use today, i.e., the airspace is divided into several adjacent volumes called *sectors*. Accordingly the area of jurisdiction covered by an ATC centre comprises one or more concatenated sectors. The traffic in each sector will be managed by a *controller team*. Each controller team performs planning and executive functions. Note that this does not mean that one person performs the planning and another performs the executive functions. The function allocation may be done dynamically and the actual number of controllers per team may vary as function of the expected workload. In effect, ultimately zero controllers per controller team would reflect the operation of a fully automatic system.

## 3. AIR TRAFFIC CONTROL

Air Traffic Control is that part of Air Traffic Management (ATM) which monitors and controls the aircraft to ensure the safe, orderly and expeditious flow of air traffic. It is a complex task, illustrated in Figure 1. It involves human controllers and machines. To perform this task, controllers rely mostly on indirect information which is: provided before the flight, sensed by ground-based installations, transponded from aircraft, computed from collated data, radioed by air crew or telephoned by other controllers. Once captured, processed, stored and sustained, this information is presented to the controller through a Human Machine Interface (HMI).

Clearly the HMI is a major component in the ATC loop. The mental grasping of the data by the human is largely dependent upon the quality of the interface to and from the "machine". Improving the HMI will make the use of automation both safer (i.e. less error prone) and more efficient (i.e. more user friendly and less time consuming to manipulate the information). It will increase the human brain's ability to ingest, understand and process more information.

The scope and complexity of ATC problems often require that the decision making process be distributed over more than one ATC sector. To this effect several controllers must co-ordinate and transfer information, resources, activities, expertise and decisions in order to attain common goals. System supported Co-ordination And Transfer (CAT) functions will ensure that the information available to the various partners is *common* and that the appropriate automated system support minimises the workload for these tasks.

## 4. USER REQUIREMENTS

Individual persons travelling or those forwarding freight are the users of the air transportation system. They ask for a product with a *predictable* and *reliable* performance at a cost which is as low as possible. The

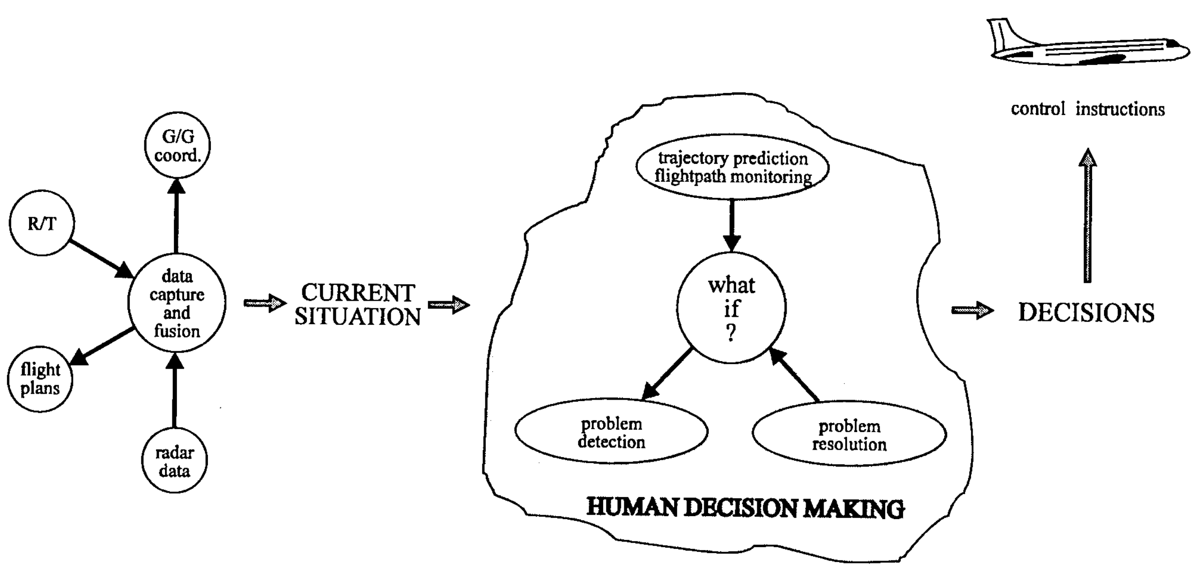



Figure 1 Human decision making process

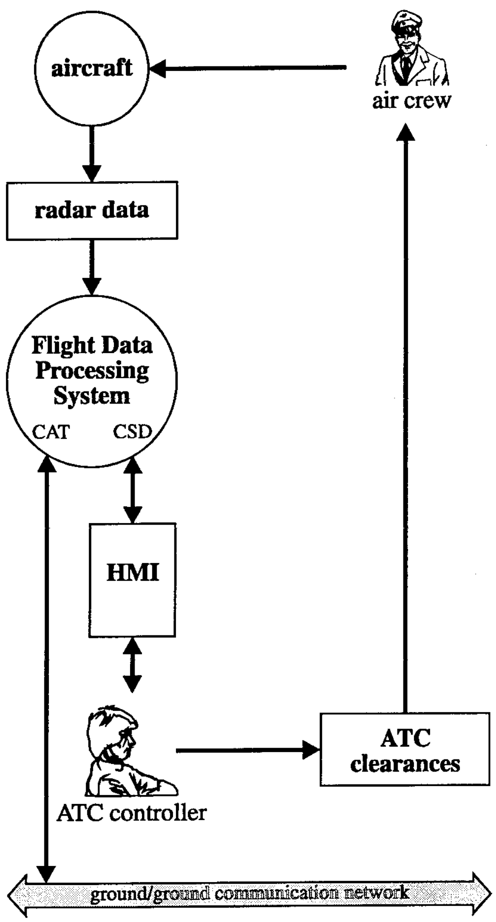



Figure 2 Basic air traffic control loop

aircraft operators are the direct users of the ATM system. To provide the public with the services requested, they want to fly from A to B *when* they want and *how* they want at a *cost* which is as low as possible.

These user requirements can be translated into a capacity requirement of the ATM system. Insufficient capacity, in particular at peak periods, will lead to traffic delays. If this is unavoidable, the associated penalty on the *direct operating cost* for the affected flights should be minimised. The element of *indirect operating cost* has an impact on the user demand for capacity as the users will not accept an increase in capacity at *any* cost. Therefore a cost/benefit analysis will be required for any proposed increase of capacity whether achieved through extension of the ground infrastructure and/or additional airborne instrumentation.

## 5. THE PRESENT SITUATION

During an IFR flight from A to B, the safe and expeditious progress of the flight is constantly ensured by ATC. To that effect the total airspace is divided into ATC sectors which constitute contiguous volumes of airspace with vertical as well as horizontal boundaries. Area Control Centres (ACCs) and terminal control facilities thus comprise upper and lower airspace sectors, as well as Terminal Manoeuvring Areas (TMAs) which constitute the lower airspace around an airport. In each sector an executive controller is in direct contact with the air crew of all aircraft for which he or she is responsible. The longer term planning is done by the planning controller possibly helped by further assistants.

This airspace structure evolves continuously. As the number of aircraft a controller team can handle is limited, the increase in air traffic resulted in a reduction of the volume airspace for certain highly loaded sectors, leading to an equivalent increase in the number of sectors that the aircraft have to fly through.

Today the point has been reached where a further reduction of the volume of airspace per sector does not increase the overall capacity. This is due to the increased workload associated with the co-ordination with neighbouring sectors. To avoid the overloading of these sectors flow control restrictions have been brought into force which has resulted in the allocation of "*slot times*" for flights through such areas in busy periods. A capacity limit has been reached!

Traffic forecasts for the next ten years indicate an average annual growth in demand of four percent. Thus the question to be answered is simple: "How can we adapt the current ATM system to move 40 % more traffic by the year 2005?"

In the given system context, a further increase in capacity can only be obtained through *an increase in the efficiency of the controller team* such that, for an equivalent workload, more aircraft can be controlled at the same high level of safety.

## 6. THE ATC "*DREAM*" SYSTEM

The ATC "*dream*" system provides a global optimisation for all air traffic from push back at the airport of departure until the engine shut down at the airport of arrival, while taking into consideration the interests of all parties involved. Passengers expect a safe arrival and adherence to the published schedules; operators want to effect the flights at minimum cost and the public authorities want to minimise the (detrimental) impact on the environment. It is clear that such a global optimisation is a very complex issue with many conflicting requirements. The compromises sought will have to consider, as well as political considerations and technological capabilities, the cost-benefit aspect of the

possible solutions. As this last aspect has a direct impact on the demand for air travel and its efficiency as a whole, we all know that today we are still far away from this dream and that there is much to be done.

## 7. THE DECISION MAKING LOOP

In a simplified form, Figure 2 depicts the basic decision making loop in today's ATC systems. The air crew provides flight director, auto-pilot and auto-throttle inputs assisted by the Flight Management and Control System.

Aircraft positions are tracked by radar systems. On the ground, in the Flight Data Processing System, the 3D positions of aircraft are linked to available flight plan information and the compiled "*current traffic situation*" is presented to the controller. On the basis of this information the controller builds in his mind a representative picture of the observed traffic. He then estimates the probable evolution of the traffic, identifies potential problems, elaborates tentative solutions, evaluates their likely consequences, decides on the implementation and communicates the instructions to the air crew. The updated "*current traffic situation*" is periodically reconsidered and the loop is repeated.

The actual decision making process is performed in the *mind of the controller on the basis of information resident there.* Although the processing capability of the human brain in the field of decision making is virtually unrivalled, the capacity of the communication channel to transfer information to and from the brain is very limited i.e. *to a few bytes per second* (Reference 3). As a comparison, the communication between machines can be easily one million times faster. Adding more generators of information to the HMI, e.g., automated decision making aids, will put a further load on this low capacity communication channel. This fact is of paramount importance in the design of the Human Machine Interface (HMI) and the integration of automated DMAs into the control loop.

The introduction of automated help will only find operational acceptance when the communication capacity of the HMI does not become overloaded. The proposed DMAs try to achieve a reduction of the flow of basic information by filtering problem/non-problem aircraft and the introduction of efficient multi-sector planning tools to avoid sector overload and complex traffic situations. The additional overhead in flow of information because of the latter modules must be minimised in order to achieve an overall increase in the number of aircraft that can be handled by the controller.

## 8. OPERATIONAL NEED FOR DMA's

The number of flights that a controller can safely and efficiently handle is limited by the mental and physical workload characteristics of the human being. Consequently he is one of the limiting factors in the control loop. Already today in some en-route sectors controllers are faced with a large number of aircraft, e.g., in 1993 in the "Brussels-West" sector in UAC Maastricht, 36 aircraft were "on the frequency" simultaneously. Under such conditions controllers can only manage the traffic by minimising the R/T load per aircraft. This is sometimes achieved by requesting the neighbouring sectors to inform the pilots not to make the "initial call" when entering the sector. Such a working method does not particularly create a comfortable situation on the ground nor in the air and the availability of an air-ground data link for the exchange of routine messages would be of great assistance under these circumstances. Moreover, through appropriate airborne installations, the automated ATC system could also check if the pilot had indeed selected the correct VHF frequency for communication, etc. However in the short term, the only practical solution is the integration into the flight data processing system of an efficient, on-line multi-sector planning function to smooth the traffic peaks and avoid overload situations.

In Terminal Manoeuvring Areas (TMAs) efficient on-line management of air traffic can also lead to tangible improvements. The ATC capacity for inbound traffic is often limited by the capacity of the traffic convergence point, i.e. the runway. Today, at busy international airports controllers often land 37-38 aircraft per hour whereas the theoretical capacity for the particular sample of traffic is one or two aircraft lower. It is clear that in this case, automated system support can never increase ATC capacity without an agreed reduction in minimum separation standards. However it has been demonstrated that through the use of an efficient Arrival Manager the number of potential conflicts can be reduced by 60% and also, as a consequence, the complexity of the traffic situation. In addition, a potential savings of fuel of up to 25 percent could be possible within a radius of 130 nm from the airport without degrading the capacity (Reference 4).

Although individual problems can be tackled by independent solutions an integrated approach will be more efficient from a human factors point of view. In the supervisory control environment three main concepts are usually encountered (References 5 and 6): In order to perform their task, the air traffic controllers must be able to:

- *perceive the system state and evolution.* Humans build their perception of the present situation and of its evolution using mental representations and look for

context-related cues in the environment;

- *act on the system when needed.* Interface design must be oriented towards action support and therefore integrate the human cognitive processes related to action. Controllers build a solution as soon as they detect a problem. Planning is central to their activity. Consequently the focus must move from tactical to strategic control;

- *co-operate within the team.* In ATC, pressure of time, traffic demands and/or limitations of cognitive resource such as memory, force the controllers to develop an efficient resource management.

From the above it is clear that, to accommodate the increasing traffic demand, automated system support functions are essential tools to assist the human. This means that *task sharing between humans and machines becomes inevitable.* The decision making aids must be designed and integrated in such a way that an optimum symbiosis is ensured between the capabilities of the human and those of the machines. Therefore, to make efficient use of the capabilities of this "*extended controller team*", resource management is essential to co-ordinate in time *who* does *what, when* and *how.* Note that the existence of an extended controller team will have a considerable impact on the training of the controllers to obtain the appropriate knowledge and competence to perform efficiently in the new ATM context.

From a safety point of view, the task sharing aspects in the "extended controller team" require special consideration since complete automation of a function requires that all possible situations can be predicted and analysed. This is patently impossible in ATC: the local context cannot be completely controlled and hence, at any time, the human is required as a safety mechanism (Reference 7). Consequently the interaction between the human and the automated assistance requires attention with respect to "*reversibility*", meaning the possibility to revert to the fall-back mode of non-automated functioning whenever needed. Indeed practice shows that this is often possible in the beginning of the development, but is soon rendered impossible by the general need for efficiency.

Three domains of automated help can be easily identified: human-machine interface, co-ordination support and decision making aids:

### 8.1. Human Machine Interface (HMI)

The mental acquisition of data by the human being is largely dependent upon the quality of the interface to and from the "machine". Typically the controller is presented with dynamic displays intended to convey a picture of the current air traffic situation. This composite display will feature correlated radar and flight plan data, the route structure map and heavy weather indications. The controller inputs data in order to record decisions or to facilitate the capture of data.

Data input and display have been greatly improved over the years, from the initial paper strip board, to the present correlated, synthetic radar display with input devices (e.g. keyboards or trackerballs). Several research programmes address the HMI issue, one of which is EUROCONTROL's Operational Display and Input Development (ODID) programme (Reference 8). In the EURET programme, the Commission of the European Communities and the SWIFT consortium are working on the detailed specifications for the future Controller Working Position (CWP), the definition of the CWP characteristics and assessing a suitable human Machine Interface (Reference 9). The backbone of these programmes is the use of high resolution colour displays using "*windowing techniques*" for data display and the "*mouse*" as the major input device.

Above projects concentrate mainly on the *quality aspects* of the HMI, i.e., how do we present the information available in the flight data processing system in the most efficient and elegant way. *Quantitative aspects,* such as precisely what information should be generated and displayed in order to move as many aircraft as possible through a given airspace, are not directly addressed.

### 8.2. Co-ordination and Transfer (CAT)

ATC problems, scope and complexity often require that the decision-making process be distributed over several controllers, possibly using several sub-systems which may be geographically separated, but which must co-ordinate to share their information, resources, activities and expertise in order to attain (common) goals in what is generally a dynamic and uncertain environment.

Generalisation of controller-to-controller telephone lines has been the first step, followed by system-to-system ground/ground data link (e.g. OLDI (On-Line Data Interchange) messages). Automation of the inter sector/centre co-ordination will relieve the controllers of a significant workload, and will permit a longer horizon for planning, thereby enabling the "*multi-sector planning*" concept.

Recognising the need for a step by step implementation and for the concurrent support of various performance levels in Europe, the SYSCO Task Force has been established to define the guidelines for an implementation based strategy. The discussion on CAT

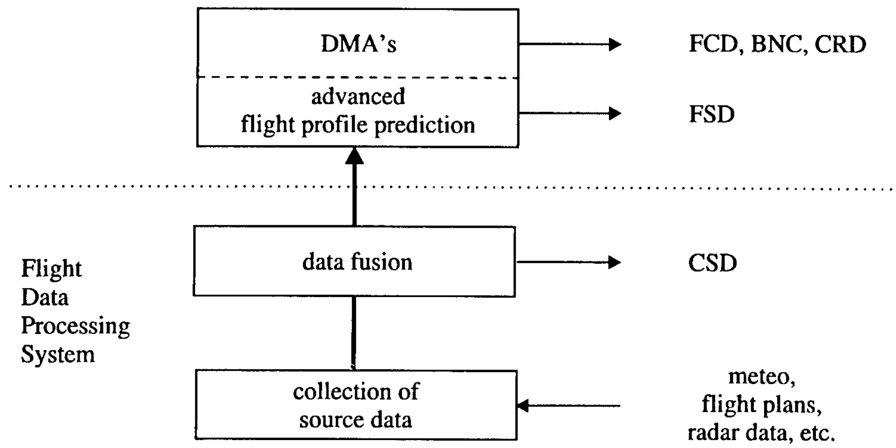



Figure 3 Structure of ATC information layers

is outside the scope of this paper but further details can be found in Reference 10. The ODID IV simulation experiments carried out at the EUROCONTROL Experimental Centre in Bretigny, France in September 1993 already contained an initial illustration of the impact of the SYSCO concept on the controllers HMI.

### 8.3. Decision Making Aids (DMA's)

As mentioned earlier, decision making, in order to ensure a safe, orderly, and expeditious flow of air traffic, requires that the controller projects the current situation in order to determine his or her (future) actions. These actions will be conditioned by concerns for aircraft safety and ATC efficiency. The set of *Current Situation Data* (CSD) is the basis for the decision making process. A ground-ground communication network ensures efficient sharing of information among different ATC sectors and centres. This sharing of information ensures that the CSD is available throughout the entire ATC chain. As ATC is a distributed process, it is of prime importance that the information available to the controllers is *COMMON*, i.e., that when one person or system module speaks about "the man with the little green hat at the other side of the street", every other one involved will identify the same man. To achieve this, support from adequate ground/ground communication networks with sufficient capacity and response times is essential. Also the availability of an air/ground data link would be very beneficial.

Through adequate training and expertise, in a fixed routing system, human prediction of the future situation is (very) good at sector level. However, due to the volume of information to be processed, human prediction is much less at multi-sector level. In analogy with the set of *Current Situation Data,* the basis for DMAs will be the provision of a common set of *Future Situation Data* (FSD) to support multi-sector planning functions.

Today, some assistance is being provided to the controller to plan ahead. Local flight plan data processing, updated either by radar tracking or by controller inputs, generates a better display of the Current Situation Data. Aircraft performance databases have been developed enabling flight plan processing improvements to be made. Winds aloft have been introduced, even if still in a coarse manner, thus permitting more accurate mental projection. In a next step decision making aids will be introduced, being an important aspect of the operational concept defined in the EATCHIP Phase III Work programme. Present high computing power, good aircraft performance data, sufficient environmental data (e.g. weather, winds, airspace management constraints) and a knowledge of the air crew intentions (through updated flight plan data) will permit useful (for the purposes of decision making) trajectory prediction data to be produced.

DMAs may be defined as to cover all aspects of automated assistance made available to air traffic controllers based on *trajectory prediction* and *flight path monitoring.* These DMAs will help to meet the user requirements by increasing ATC capacity and/or minimising the operating costs for the airlines at the same time. The introduction of advanced decision making aids will affect the working environment of the individual controller team in several ways.

There are several DMA features. The first feature is the provision of the *Best Next Clearance* (BNC). If the current progress of a subject aircraft is not in line with the plan contained in the Future Situation Data (FSD), the automated system will generate an advice to the

controller on how to bring the FSD and the actual situation into line again. The BNC advice is generated through considering the resources required to stabilise the situation (in effect mainly the workload required in the cockpit and on the ground), the user preferences and the best possible level of safety. In practice the Best Next Clearance consists of any combination of standard ATC clearances. The main source of information to generate the Best Next Clearance will be provided by the multi-sector planning tools, e.g., the local flow management tools such as Departure and Arrival managers, and by Conflict Monitors which are discussed below.

The second feature is the availability of a *Filtered Conflict Data* (FCD) function. This is a kind of extension of the "altitude filter" already implemented in several controller working positions. It allows the filtering of non-problem traffic from the direct attention of the controller. Depending on the traffic situation, the FCD function may lead to a considerable reduction of information to be processed by the controllers (Reference 11).

The display of *Conflict Risk Data* (CRD) is the third feature that results from the introduction of DMAs. It allows the controller to monitor the validity of the ATM plan, the impact of the Best Next Clearances and, in general, the effect of the actual clearances delivered to the aircraft. The CRD provides the controller with information regarding the "*conflict state*" of the traffic. The conflict state summarises the characteristics of potential conflict situations in terms of "*when?*", "*where?*", "*how close?*" and the *predicted evolution* of these parameters based on an analysis of the observed radar tracks and/or airborne data received through

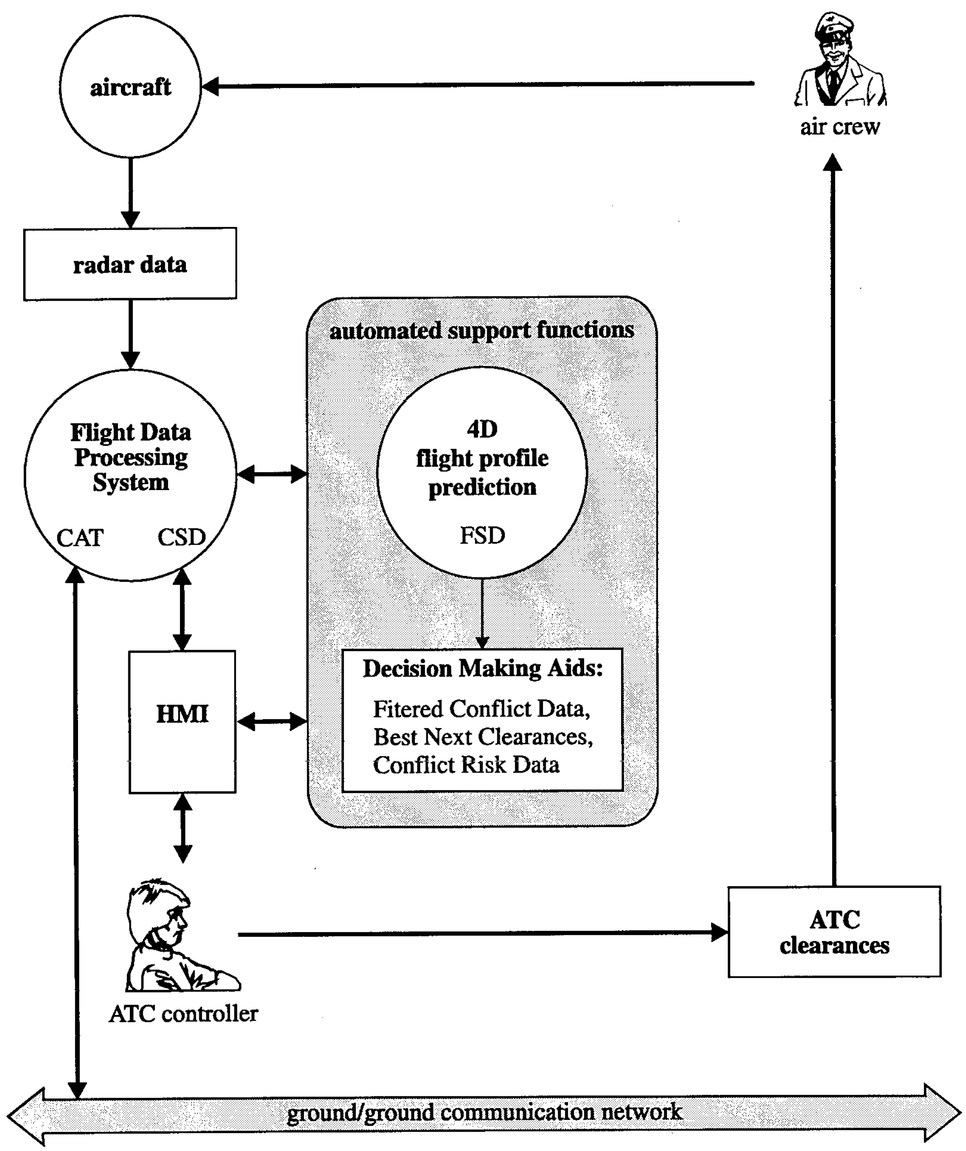



Figure 4 "Fail-safe" integration of automated support functions

air/ground data link channels.

Ultimately, automated decision making aids will achieve an overall *reduction of the situation complexity* and the controller's *situation awareness* will be reinforced. Note that situation awareness does not only concern the traffic situation. It is also related to task awareness (*"what has to be done next?"*), to resource awareness (*"how can this be done?"*) and team awareness (*"who is in charge of the task now?"*) (Reference 12).

## 9. INFORMATION LAYERS

The relation between the decision making aids and the common Flight Data Processing System is further illustrated in Figure 3. It shows the structure of the different layers of information. The two bottom layers represent the processing of information as performed in the present Flight Data Processing systems. The relevant information is gathered from the different sources, fused and subsequently displayed to the controllers. These processes include the tracking of radar data, flight plan - radar track correlation, etc. Besides this basic information the decision making aids require a prediction of the future. The more accurate this prediction is, the more useful and reliable the information generated by the DMAs will be.

## 10. IMPLEMENTATION OF THE CONCEPT

Figure 4 illustrates how help from automated tools could be integrated within the basic control loop in a *"fail-safe"* manner, i.e., if the tools fail for what ever reasons, the basic operational control loop will continue to function correctly. The *Current Situation Data* (CSD) produced by the Flight Data Processing System feeds the *automated support functions*. The *Future Situation Data* (FSD) is computed on the basis of the information in the CSD and the expected evolution of the relevant parameters. The ground/ground communication network ensures that the FSD information is *common* for the different users. Subsequently, common CSD and FSD constitute the required information data base for the decision making aids such as Filtered Conflict Data , Best Next Clearances and Conflict Risk Data. Depending on the specific tasks the controller has to perform at a given moment, e.g., planning or executive functions, through the HMI, assistance can be asked from the automated tools. The Co-ordination And Transfer process makes the same information available to other controller teams thus enabling a *multi-sector planning* capability.

The advantages of this implementation strategy are obvious. The automated support functions are only loosely coupled to the basic ATC loop thereby providing *fail-safe* operation. Controllers will only obtain or be given the information requested thereby deciding dynamically on an individual basis to what extent they want to be assisted by the automatic tools. In this way the controllers can control directly the amount of information that is generated by the DMAs to avoid overflow. The integration of the use of automated system support in the working rules of the controller cannot be achieved through a "Big Bang" approach. Experience will have to be gained gradually, thereby continuously adapting and improving the interaction between the controller and the assistance provided.

## 11. HIERARCHY OF DMA's

In the ATM system automation support is provided at different levels. Up to several months before the actual departure, a flight is introduced into the system through the Initial Flightplan Processing System (IFPS). From then on it is considered in the Central Flow Management Unit (CFMU). The task of the CFMU is to prevent the global ATM system to become overloaded. To that effect it allocates *"slot times"* for departures. IFPS and CFMU are ATM functions that ideally cover the whole of the ECAC member states. Once an aircraft starts moving it will be subject to Air Traffic Control.

The automated support functions and decision making aids discussed in this paper are limited to the part of the flight that will be affected by ATC. This is illustrated in Figure 5. On its flight from airport A to airport B the control of the flight might pass through various ATC sectors and/or centres. On-line, local flow control is a multi-sector planning tool that manages the traffic over several centres/sectors in line with the user requirements. It will try to advise the controllers in the most efficient way and how to avoid traffic peaks that may overload certain geographical convergence areas. Typical examples which are already in operation are Departure and Arrival Managers. From the problems observed in busy en-route centres today, like the UAC Maastricht, it can be concluded that the introduction of such tools is already very desirable. In general these DMAs will communicate with the executive controller through the advice in the form of a Best Next Clearance.

Another application area for DMAs is the inter-sector co-ordination task. Controllers of consecutive sectors have to agree on the hand over conditions of an aircraft before it enters the next sector. If the standard conditions as described in the "Letters of Agreement" cannot be met because of other traffic, a negotiation procedure is started between the two control teams

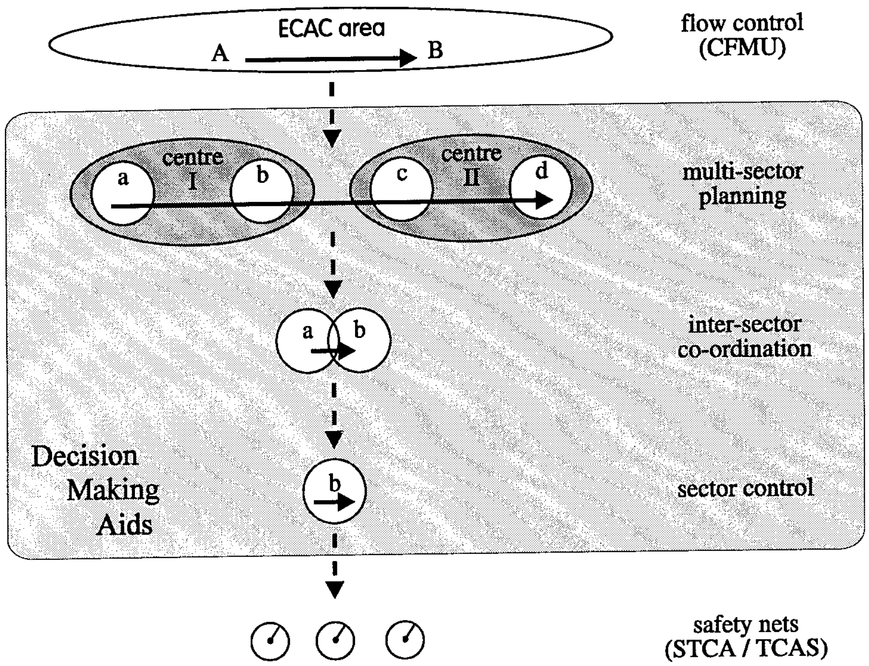



**Figure 5 Hierarchy of DMA's**

involved. This can add seriously to the workload. Automatic conflict detection in the Area of Common Interest (Reference 10) can help to propose hand-over conditions for the aircraft that are acceptable by the controller team in the next sector without further negotiation.

At sector level, the Filtered Conflict Data (FCD) function selects for the controller those aircraft that are not to be considered in a conflict search with the selected subject aircraft nor will have any effect on a possible resolution strategy (Reference 11). The Conflict Risk Data (CRD) informs the controller on the current conflict state of the aircraft under control and the predicted evolution of the conflict state based on the observed trend.

Finally a set of safety nets exists in the air (e.g., TCAS) and on the ground (e.g., Short Term Conflict Alert (STCA)) which become active when the normal ATC system has failed to provide a sufficient level of safety. These should not be considered as decision making aids. However it is to be noted that "false alerts" triggered by these systems can increase the controller workload considerably.

As all the above tools are based on the same common Current Situation Data and Future Situation Data a hierarchy can be identified in the above set of tools. The FSD comprises a prediction of the medium term future based on a set of system plans which are kept up to date by the controller. Any action of the controller or unplanned action of the pilot will invalidate this medium term future and change the FSD. In effect it may invalidate the Best Next Clearances and/or proposed handover conditions. Consequently it is in the interest of each individual DMA to advise the controller in such a way that *the resulting traffic situation has the lowest chance to trigger new actions of controllers and pilots*. A stable FSD is of paramount importance for useful operation of DMAs. In other words, the multi-sector planning tools should advise the controllers through the Best Next Clearances to manage the traffic in such a way that tactical control actions at sector level are minimised. In the Operational Concept this is referred to as the "*Minimum Resources Solution*".

In conclusion, the DMAs should be considered as *an integrated package of tools* that ensures optimum consistency in ATM from sector to multi-sector level and NOT as individual system components.

## 12. COMPUTING THE FUTURE SITUATION DATA

The ATC "dream" system provides conflict free flight paths to all aircraft from brake release until touch down. Where are we now?

Today's modern Flight Data Processing Systems contain trajectory prediction modules for two application areas. The first supports flight planning. It computes the Estimated Times of Arrival (ETAs) over waypoints on the basis of planned routes and air speeds. Aircraft

performance is approximated per class of aircraft on the basis of average, empirical data. Depending on the level of sophistication, the predicted trajectory will be updated when the estimated error on the ETAs is more than one or a few minutes. The second application area is a Safety Net function which will become active when the normal ATC loop has failed. A trajectory is predicted up to a few minutes ahead in time mainly on the basis of the aircraft speed vector extracted from observed radar data.

In the concept of decision making aids an optimum plan is established by the automated Flight Data Processing System. To that effect trajectory prediction, conflict detection and , to a certain extent, also conflict resolution modules are required. What can be achieved?

## 13. THE TRAJECTORY PREDICTION PROCESS

The trajectory prediction function is the key component in the production of the set of Future Situation Data. The process is depicted in Figure 6. In effect the process of flight profile prediction is similar to the operation of a flight simulator but then in fast time. The pilot, his or her intentions and operating procedures of the aircraft are contained in the system plan. To that effect the system plan holds a detailed description of how the aircraft will be flown by the pilot in the given ATC context. From the initial conditions the trajectory engine module executes the system plan in "fast time" using the performance characteristics of the specific aircraft and the description of the meteorological environment in which the flight is operated. The 4D-flight profile is the result of this operation. The set of 4D flight profiles of all aircraft to be considered comprises the core of the Future Situation Data (FSD). It is clear that the reliability of the FSD is directly related to quality of the information provided by the decision making aids.

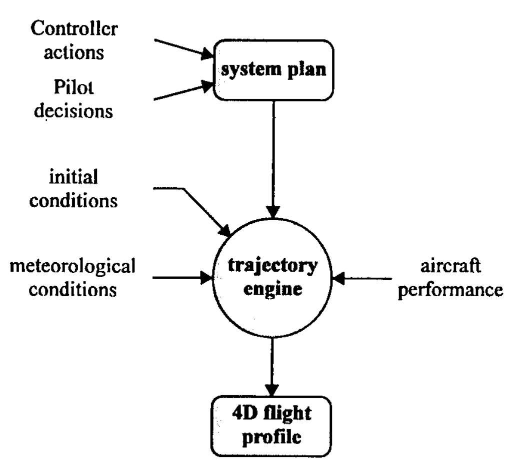



Figure 6 Trajectory prediction

### 13.1. Uncertainties and perturbations

Parameters that affect the reliability of the predicted trajectory can be divided into two categories. The first one is related to the actual flight profile calculation process. Uncertainty of the initial conditions like position and airspeeds may cause a shift of the computed profile in space. Uncertainty of the aircraft mass may have a considerable impact on those parts of the flight profile that depend on engine performance such as climb and acceleration phases. Uncertainty of the performance characteristics of the aircraft, like engine thrust and aerodynamic drag, affect the altitude profile and phases of flight with changing airspeed. Uncertainty of the meteorological conditions like wind and temperature profiles and the barometric pressure at sea level, affect the subject flight but will cause identical perturbations to other aircraft which operate in the vicinity of the subject flight. Therefore their effect on the overall system stability will depend on the specific traffic situation. An extensive discussion on the impact of the individual parameters on the computed flight profiles is presented in Reference 13 for individual aircraft.

The second category of perturbations has an impact on the reliability of the predicted flight profile which is considerably greater. It relates to the human actions of pilots and controllers. Although the system plan is compiled from a data base specifying the aircraft operating procedures as recommended by the individual airlines, it can never be ensured that pilots will indeed follow these procedures. Actual selected speed profiles and acceleration/deceleration methods may differ considerably from those recommended or even filed in the official flight plan. Also, in particular, the estimate of the optimum top-of-descent point may differ considerably from one pilot to another. Nevertheless in general an aircraft will follow the planned route and cruise at the cleared flight level. Consequently the air traffic controller constitutes the main perturbing factor for the computed 4D flight profile as, at any instance, he or she can change the route, cruise level and airspeeds as a function of the overall traffic situation. In other words: *the main user of the information generated is also the largest perturbing factor.*

### 13.2. The "Volume of Protection"

Assume that, on the basis of the information provided in the system plan, aircraft performance model and the meteo data base, a 4D flight path has been computed that comprises a series of (t,x,y,z) data points. If the actual flight conditions do not precisely match the assumptions made in the trajectory prediction process, the actual aircraft positions will differ from the predicted ones. The uncertainties are summarised in the "Volume of Protection" (VOP). The VOP at time, t, defines the range of possible aircraft positions at that moment. The minimum size of the volume of protection is defined by the minimum separation criteria in the horizontal and vertical plane. In reality the size of the VOP will be greater than those minimum dimensions due to the uncertainties that affect the prediction of the reference trajectory.

When, at a later stage the "conflict detector" module finds an overlap in space between the Volumes of Protection of two aircraft a "potential conflict" situation is detected and further processing is required such as conflict risk analysis, etc. Whether the detected conflict will actually be presented to the controller may depend on various factors, e.g., time to the conflict, minimum distance, conflict risk , observed trend, etc. It is paramount that the *size of the VOP must be as small as possible* in order that the maximum number of aircraft can pass through a given volume of airspace without triggering unnecessary "false alerts".

The probability distribution of the aircraft position within the VOP will have systematic and random components depending on the contributions from the individual uncertainties, e.g., if the estimated take-off-weight of the aircraft differs from the actual one, this will result in a systematic error contribution over the entire flight. On the other side, the accuracy with which the on-board automation can maintain a selected air speed will result in a random perturbation with a time constant defined by the characteristics of the Auto-Throttle function in the aircraft.

To a certain extent systematic perturbations can sometimes be estimated through the monitoring of the actual progress of the flight and the subsequent comparison of the predicted and observed flight paths over a certain period of time. It is clear that the availability of air/ground data link in the future will be of great advantage.

Three different methods to generate trajectories for the Future Situation Data exist, each with their own merits and disadvantages. The first two are entirely "ground based" and referred to as "*open loop*" and "*closed loop*" systems. The third approach assumes that the aircraft computes the flight profile and communicates it to the ground system for further processing. In this concept a high capacity air/ground data link which is capable of supporting a negotiation procedure between the aircraft and the ground based ATC Flight Data Processing System is a prerequisite.

### 13.3. "Open loop" trajectory prediction.

This method is similar to the way in which ETAs are computed in the current Flight Data Processing Systems. A reference trajectory is computed on the basis of the information provided in the system plan,

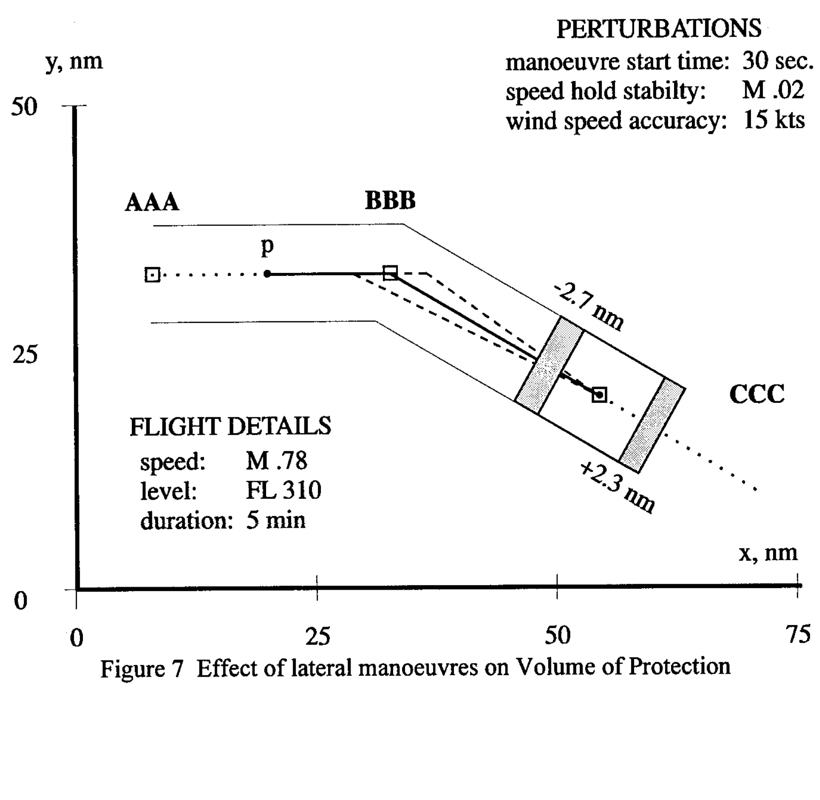



Figure 7 Effect of lateral manoeuvres on Volume of Protection

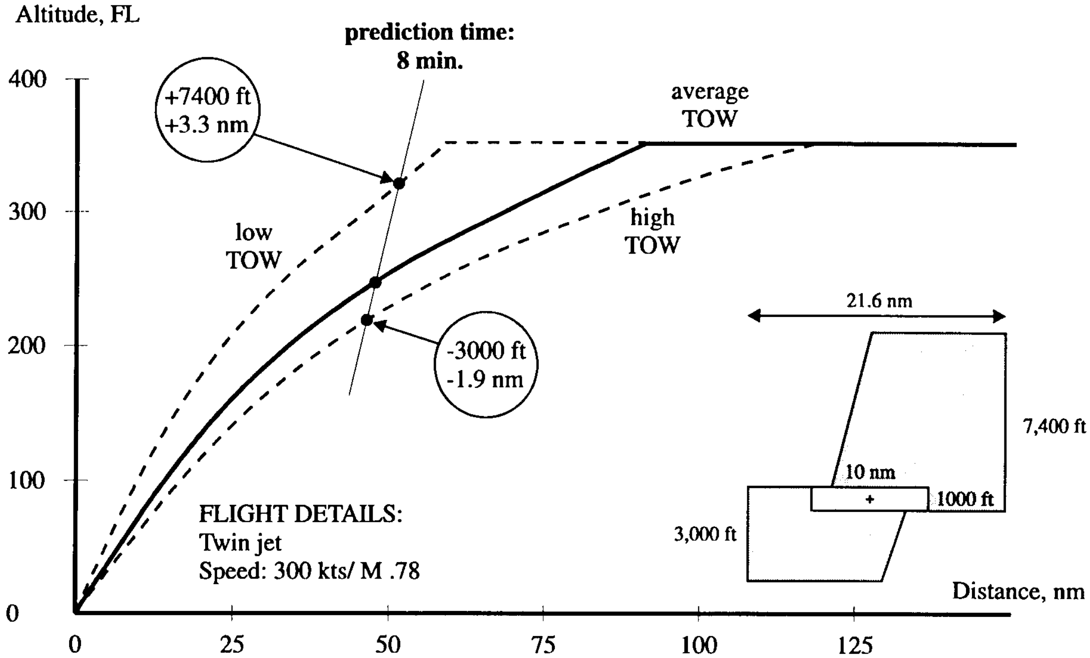



Figure 8 Effect of mass uncertainty on Volume of Protection

aircraft performance model and the meteo data base. Then a "Volume Of Protection" is defined around each 4D data point in the reference trajectory. Which parameters are to be considered and what is their impact?

### 13.3.1. Impact of lateral manoeuvres.

In Figure 7 an aircraft is shown on its way from point AAA to CCC via BBB. The aircraft is flying in stable cruise conditions at Mach .78 and Flight Level 310. At BBB the route centre line turns 30 degrees to the south. The estimated duration over the route centre line (solid black) from the present position, "p", to CCC is 5 minutes of flight. The diagram shows the "Volume of Protection" around the aircraft for the predicted situation at waypoint CCC. The following possible perturbations are assumed. The wind speed is known with an accuracy of 15 kts. The speed of the aircraft can be maintained with an accuracy of Mach .02 and the pilot will initiate the turn from leg AAA-BBB to BBB-CCC with an accuracy of 30 seconds. The white rectangle at CCC represents the minimum separation requirement of 5 nm in lateral and longitudinal direction. The grey area indicates the increase of the Volume of Protection due to the perturbations for the 5 minute prediction time. The perturbations only affect the longitudinal component of the flight as it is assumed that the pilot will maintain the aircraft with 5 nm of the route centre line. In the vertical plane, the Volume of Protection extents to 1000 ft above and below the cleared flight level. The contribution of the uncertainty of the start of the horizontal manoeuvre amounts to +0.3 nm in the case of the short cut to -0.7 nm in the case delayed start of the turn.

In the example it is assumed that the target speed of M .78 is known precisely. Uncertainty about this would further increase the Volume of Protection. The way around this problem is to perform the profile prediction on the basis of observed ground speed rather than aircraft speed and wind estimates. In the case of unconstrained, level flight in a stable environment, this approach leads to smaller Volumes of Protection (Reference 14).

### 13.3.2. Effect of vertical manoeuvres.

The effect of vertical manoeuvres on the extent of the Volume of Protection will be illustrated by two examples. The first involves a twin jet in climb. The prediction is made shortly after take-off and the Volume of Protection is evaluated for 8 minutes into the future. At the start of the prediction the aircraft is climbing to a cleared level of 35,000 ft. The Take-Off Weight (TOW) of the aircraft is not known precisely. Figure 8 illustrates the range of possible flight profiles in the vertical plane. The prediction is made on the basis of an average take-off weight (solid black line) and a constant climb speed profile of 300 kts IAS/ M .78. The climb profiles for a low and a high take-off weight are also shown with the respective aircraft positions after 8

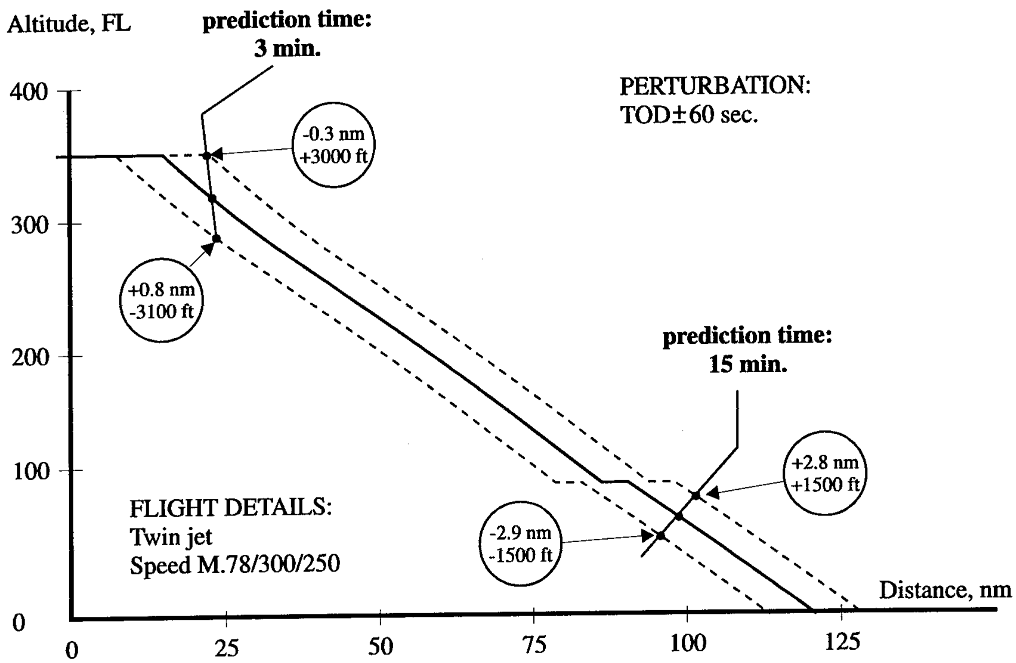



Figure 9 Effect of vertical manoeuvres on Volume of Protection

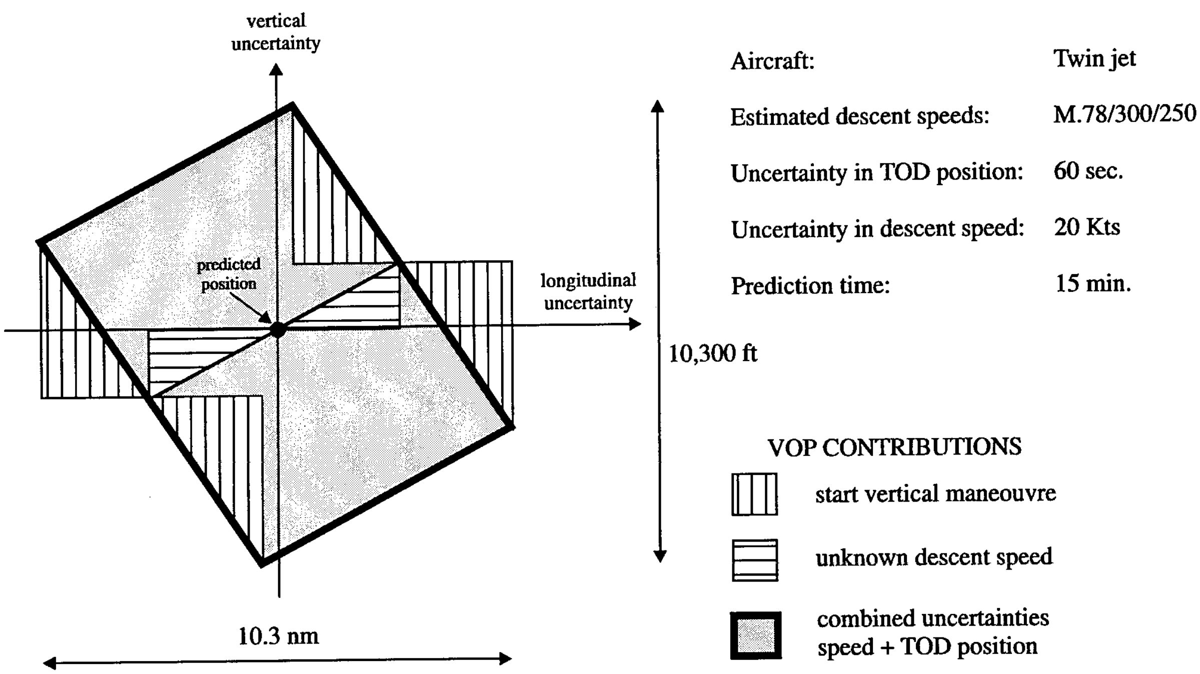



Figure 10 Effect of TOD point and descent speed on Volume of Protection

minutes prediction time. The impact of the uncertainty on the exact TOW is apparent. The diagram also shows the volume of protection after 8 minutes prediction time (grey area) with the separation minima as a reference (white rectangle). The same uncertainties for aircraft and wind speed are used as in the example for lateral manoeuvres (Figure 7).

For flight profile predictions, including cruise/descent phases of flight, the start of the "Top of Descent" (TOD) is an important item that affects the size of the Volume of Protection. Within the data processing modules that produce the Future Situation Data it is never precisely known when the controller will clear the aircraft for descent, nor precisely when the pilot will

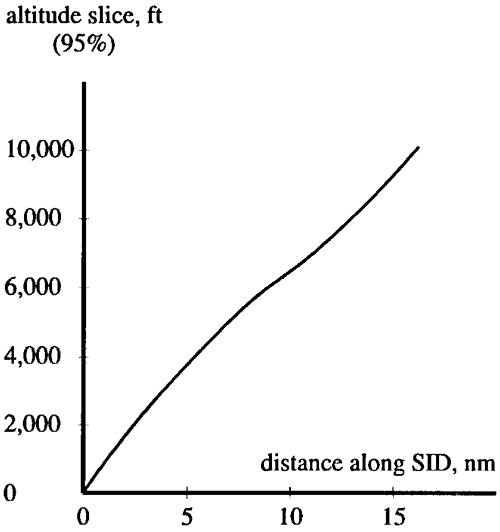



Figure 11 Distribution of altitudes along SID's (2500 flights)

close the throttles. In Figure 9 the situation is presented for a modern twin jet in cruise at FL 350 for which the TOD is expected in 2 minutes. The standard descent speed law is M .78 / 300 KIAS then 250 KIAS below FL 100. The impact of an uncertainty of 60 seconds in the TOD position is illustrated for prediction times of 3 and 15 minutes. *Note that the evolution of the resulting uncertainty is NOT linear with prediction time.*

Unlike in the climb phase, the vertical component of the flight profile is constrained in descent. Ideally at the TOD the throttles are closed. The TOD is selected such that engine power will only be applied when the aircraft reaches the decision altitude on the glide slope. During the descent the pilot can use airspeed for fine adjustment of the vertical profile. At idle power, variations in airspeed have a considerable impact on the descent performance. Figure 10 illustrates the combined impact on the volume of protection of a TOD uncertainty of 60 seconds and an uncertainty of 20 knots in the selected Indicated Air Speed (IAS). The initial conditions are identical to those of Figure 9. The uncertainties are presented for a prediction time of 15 minutes. The actual size of the volume of protection has to be increased with the uncertainties with respect to wind and speed hold capabilities and the minimum separation criteria.

Several surveys have been made to assess the predictability of flight profiles (References 16 and 17). Figure 11 depicts the variation in altitudes for aircraft following Standard Instrument Departure routes out of London Heathrow and Gatwick airports for a traffic sample comprising more than 2500 flights. At 16.2 nm along track distance the 95 % altitude band extends on the average to 10,000 ft. These results are typical and therefore a clear illustration of the reality. They confirm the theoretical examples.

### 13.4. "Open loop" trajectory prediction - "worst case" approach

The above examples illustrate clearly that, if a trajectory prediction is solely based on the data comprised in the system plan, the Volumes of Protection will increase rapidly with prediction time. Accordingly this technique is not very suitable for medium term (say 20 minutes look-ahead time) traffic planning in high density areas without losing a considerable part of the available capacity. However the "open loop" prediction technique can be applied conveniently to provide the basic information for the "filtering" of problem/non-problem aircraft. For this application it is essential to know with a high degree of certainty where, at a given time, the aircraft will NOT be. Any other aircraft that is in that area is of no concern to the subject aircraft.

For this application, the extent of the Volumes of Protection must also consider possible controller actions such as the definition of a different sector-exit point, radar vectors for conflict avoidance, speed and altitude restrictions, etc. It is clear that the VOPs increase very rapidly with prediction time but, in principle, this does not invalidate the reliable operation of this decision making aid. The only effect will be that the number of aircraft that will be filtered out will reduce with increasing look-ahead time.

### 13.5. "Closed loop" trajectory prediction

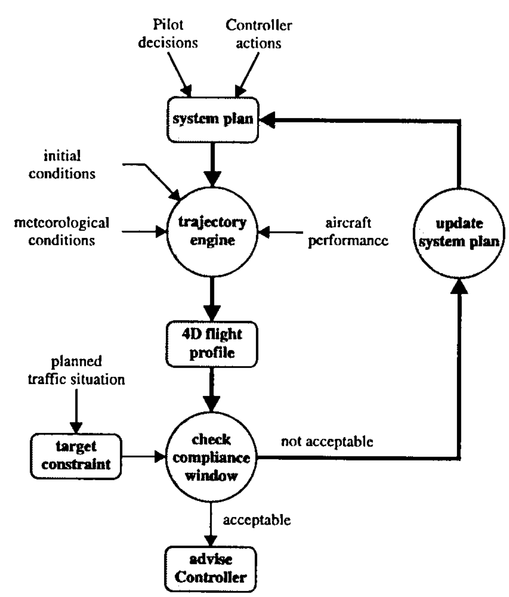



Figure 12 "Closed loop" trajectory prediction system

In the "*open loop*" approach described above, the future position of the aircraft is estimated on the basis of its *observed position* and an estimate on how the aircraft will be operated, contained in the *system plan.* In effect the future situation is *the result* of the flight profile computation. It has been described how the reliability of the predicted profiles degrades with increasing look-ahead time and, inevitably, the quality of the information provided by certain DMAs will decrease accordingly.

In contrast, in the "*closed loop*" prediction technique the future situation is defined as a *target constraint* and the system plan is modified to obtain the desired constraint (References 18 and 19). The principle is depicted in Figure 12. In co-operation with the controller, one or more decision making aids agree on a desired traffic situation somewhere in the future. This is translated into *target constraints* for individual aircraft. As in the case of the "open loop" technique, the prediction loop starts at the default system plan. The trajectory engine translates this into a 4D flight profile. Subsequently it is checked whether this flight profile matches the target constraints within a definable window, the "*compliance window*". If this is not the case, the system plan will be updated as a function of the observed discrepancy using the control parameters available. This process is continued until a flight profile is obtained that satisfies the constraints. If the current progress of the aircraft is not in accordance with the updated system plan, the controller can be informed accordingly through a "*Best Next Clearance*" advice. If the satisfactory match between target constraint and predicted flight profile cannot be obtained, the planned traffic situation will have to revised as it appears that the initial plan is not achievable.

To ensure stability, the control loop is executed every time new data becomes available, typically after each rotation of the ATC radar. As the diagram correctly suggests, pilot decisions, controller actions, inaccurate aircraft performance and varying meteorological conditions are all treated by the control loop as similar perturbations. Accordingly the "Best Next Clearance" advice to the controller adapts *dynamically* to the changing environment without further controller intervention.

This trajectory prediction and control technique makes it possible *to define accurately the desired separation criteria independently of the look-ahead time.* Therefore it is ideally suitable to manage traffic at busy convergence points e.g. as is the case for an "arrivals manager" tool where the touch-down point on the runway constitutes the convergence point. What can be expected in terms of accuracy?

### 13.5.1. CINTIA prediction and control technique

The "closed loop" trajectory prediction and control technique is applied in the CINTIA (Control of Inbound Trajectories for Individual Aircraft) module of the ZOC (Zone Of Convergence) arrivals manager (Reference 20). Many experiments have been carried out using full scale airline flight simulators manned by regular airline crews to test CINTIA's capability to predict, guide and

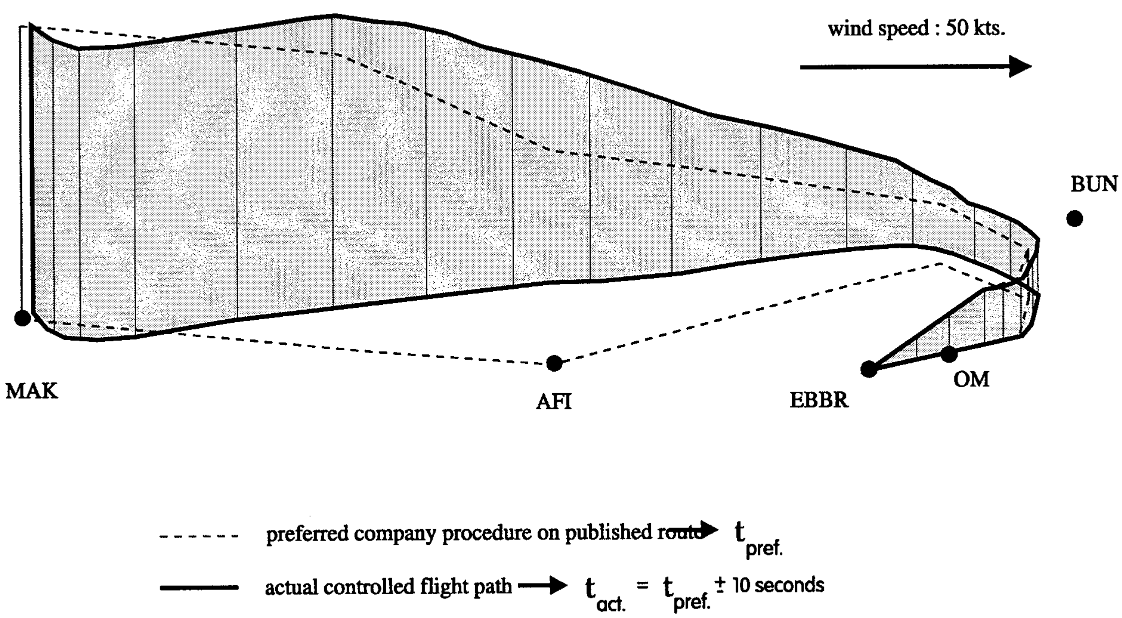



Figure 13 CINTIA's capability to control the arrival time accurately

control aircraft so as to maintain a specified time of arrival at a waypoint when being affected by large perturbations. To this effect the most complex environment had been selected i.e. the one which includes an approach to a landing runway (Reference 21). A typical experiment scenario is depicted in Figure 13. The geography pertains to an arrival route at Brussels International Airport in use at the time of the experiments. For the test the flight simulator would be positioned over the waypoint MAK at the start of the exercise. The published route to runway 25L was passed over AFI, then towards the initial approach fix BUN and it was expected that the controller would vector the aircraft to base somewhat before BUN to intercept the localiser at 8 nm from touch down. The extent of the flight path was of the order of 80 nm or 16 min. of flight under standard conditions. To complicate the experiment further, a wind vector of 50 knots was introduced, leading to an effective change in headwind component of 100 knots when turning from down wind to the localiser. The 4D reference flight path was predicted on the basis of the "*preferred company operating procedure*" for the aircraft flown over the published route. Thus the computed arrival time, $t_{pref}$ at the touch down point was the 4D constraint for CINTIA to meet. Figure 13 shows the result for a typical flight. The first perturbation was introduced accidentally by the aircrew as the flight simulator appeared to be flying in the wrong direction when it was released at the start of the exercise. The controller then simulated a potential conflict with crossing traffic over AFI and directed the aircrew onto a direct route to BUN. Subsequently the controller followed the "*best next clearances*" generated by CINTIA and transmitted these through an R/T link to the aircrew in the flight simulator.

The control parameters available to CINTIA to meet the target constraint depend on the phases of flight considered and the specific ATC environment. In the example CINTIA's control logic can be deduced by comparing the published route with the path actually flown. As speed reduction in the enroute part was not sufficient to compensate for the shortcut at AFI, the down-wind leg was slightly extended.

During several tests, different combinations of ATC perturbations were introduced. *In all cases the arrival time accuracy at the touch down point obtained through CINTIA remained in the order of 10 seconds.*

### 13.6. Summary of ground based trajectory prediction methods

Unlike the "open loop" prediction method, the "closed loop" approach constitutes a very effective means to reduce the Volume of Protection at the critical traffic convergence point to the minimum. It is clear that this will not be the case along the predicted flight profile from the aircraft's present position to the target position. In effect the size of the VOP will increase and subsequently decrease with prediction time, all as a function of the flight path complexity, viz., horizontal and vertical manoeuvres and speed changes. As will be discussed in the Sections dealing with Conflict Detection, the effective size of the VOP can be further controlled through the introduction of additional constraints at key points along the route. The interface to the controller through "Best Next Clearances" remains unchanged so that the number of constraints is completely transparent to the controller. Globally the workload and flow of information will decrease.

In many respects the CINTIA "closed loop" prediction and control technique can be considered as a ground based 4D Flight Management and Control system (FMCS). It considers aircraft performance in a similar way and also uses aircraft speed and/or flight path modifications as control parameters from which the "Best Next Clearances" are extracted. This could very well be an essential consideration in the *evaluation of the cost-benefits* for the future ATM system as the above features are ground based. Therefore they are available for all aircraft from small piston-propelled ones to jumbo jets *without any additional cost to the aircraft operators.*

### 13.7. Airborne prediction capabilities

When unhindered by any ATC constraints and assuming that the aircrew do not change their initial intentions, in modern aircraft on board Flight Management and Control Systems (FMCS) have the capability to predict the passing of an enroute waypoint with an accuracy of a few minutes. The technique applied is similar to the "*open loop*" approach described above. Without any doubt the accuracy level of the FMCS prediction is far greater than that from a ground based prediction module as many of the parameters unknown to the ground are precisely defined in the aircraft, e.g., mass, speed law, aircraft performance and start of horizontal and vertical manoeuvres. The absolute accuracy obtained is a function of the uncertainties encountered such as the errors in the meteorological database, the speed-hold capability and the navigation accuracy. A further increase in accuracy can be obtained from the application of 4D-FMCS systems which add a control loop to the "*open loop*" prediction approach to achieve predefined constraints. With the aircraft speed and/or flight path modifications as control parameters, experimental 4D-FMCS systems have demonstrated that a 5 sec. delivery accuracy, even at the touch down point, is feasible.

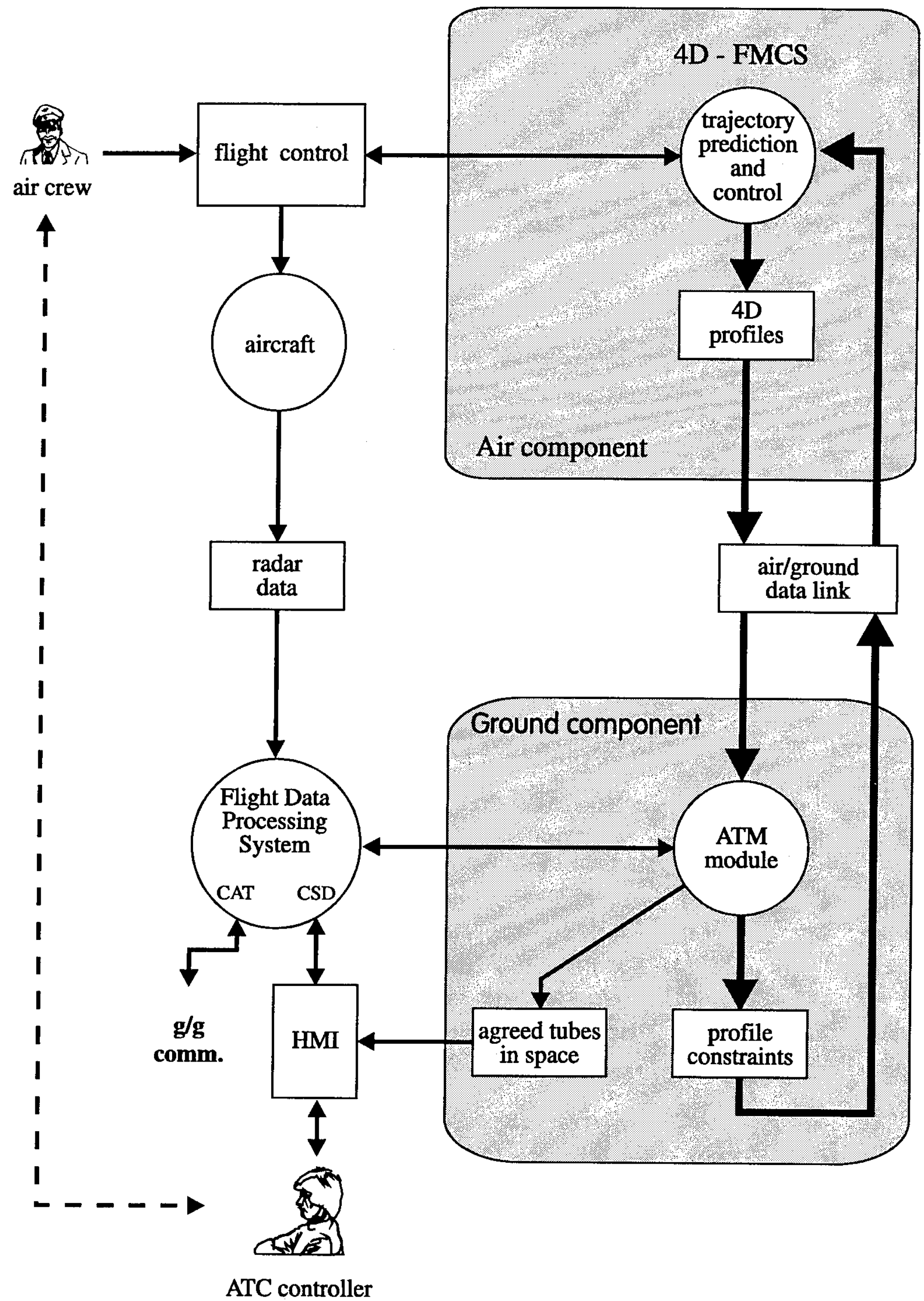



Figure 14 Use of airborne trajectory prediction and control capabilities

The advantages for ATC of a cleared, conflict free FMCS profile are obvious when the aircraft proceeds along a quiet RNAV route. The situation is different in busy areas with converging traffic. To obtain a conflict free path over a certain period the flight profile may have to be adjusted to meet several subsequent constraints which are uncorrelated. To that effect it is required that the computing capabilities in the air and on the ground should be integrated into one distributed control system. In the air the FMCS computers would define optimum flight profiles which, after being relayed to the ground through a data link, will be checked for potential conflicts. If potential conflicts are detected, constraints are defined and up-linked to the aircraft. Subsequently the aircraft will propose a modified profile matching the constraints specified. If all conflicts are resolved, through this iterative process, the aircraft is given a 4D clearance in the form of a "tube in space". This clearance will be valid for a given period and it is the responsibility of the air system to

stay within the cleared tube. The process is depicted in Figure 14.

In practice, for the stability of the ATM situation, the higher quality of the airborne flight profile prediction compared to the ground based one is, by itself, not of a great advantage. Indeed in a busy area, ATC constraints caused by other traffic constitute a considerable greater perturbation then any other element of the ATC loop. The advantage of the distributed system approach is that, through an internal control loop, the aircraft will stay *autonomously* within the agreed volume of the "tube". As the tube in space was free of conflicts the controller can forget the flight for the duration of the clearance and thereby his or her workload is reduced considerably.

Unfortunately there are a few drawbacks. In an en route environment the 4D-FMCS will use airspeed as a control parameter to keep the aircraft within the cleared space of the tube. As will be discussed later, the speed control capability at optimum cruise altitude is minimal. As a consequence, in order to stay within the clearance, the aircraft will *always have to cruise at altitudes which are below the optimum*! Secondly, in order to be able to take advantage of the airborne control loop it is essential that all aircraft managed are equally equipped with 4D-FMCS systems and high capacity data link capabilities. If a non-equipped aircraft has to be integrated into a stream of equipped ones, the size of the Volumes of Protection for the non-equipped aircraft required for a conflict free clearance will immediately have a disastrous effect on the ATC capacity.

### 13.8. Comparison with ground based 4D-flight profile prediction

The basic modules of the 4D-based, distributed ATM system as illustrated in Figure 14 are identical to those of the ground based "closed loop" approach presented in Figure 12. Only the required data link communication channel is additional. When considering the excellent ground based trajectory prediction and control capabilities demonstrated by CINTIA, it is worthwhile to compare the two approaches in more detail, as the 4D clearance approach will involve considerable cost to aircraft operators who will have to equip all aircraft with very expensive 4D FMCS systems before the future system can become effective. Also in this respect, the cost associated with the installation and operation of a high capacity, air-ground digital communication network should not be under estimated.

Consider the traffic situation depicted in Figure 15. The ATM system has computed the constraints for the three aircraft such that conflict free tubes are allocated to pass

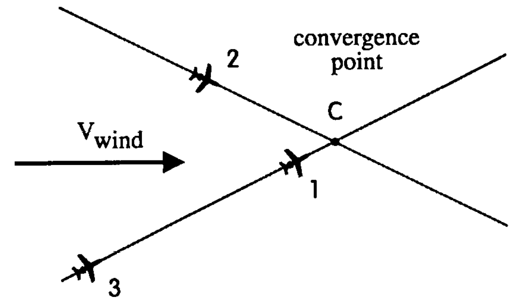



Figure 15 Potential conflict situation

convergence point "C". To achieve these clearances two conflict solution strategies could have been applied. The first one allocates tube clearances which ensure the passing of point "C" within a time window. The extent of this window depends on the expected perturbations. This strategy will not result in the maximum capacity at "C" as the time windows force larger separations between aircraft than the target ATC minima.

In the second approach the ATM system will allocate passing times at "C" such that the minimum separation criterion is met. This forces the aircraft to pass "C" at *absolute* times. Although it has been demonstrated that this is practically feasible, the consequence is, however, that a considerable part of the control potential available in the operational flight envelope of the aircraft has to be reserved to maintain the clearance. Accordingly it is not available to the ground ATM system for the global optimisation of the traffic. Also in the case of an inaccuracy in the predicted wind, all aircraft will have to compensate for the wind error in an identical way to maintain their 4D clearance.

In an enroute environment, aircraft which maintain a conflict free 4D tube clearance on an RNAV route can reduce the workload of the controllers considerably. By itself this leads to an increase in ATC capacity *if the number of aircraft under control is the limiting factor.* However when the air traffic density or airspace are the limiting factors, the situation is completely different, especially if not all aircraft are equipped with 4D navigation capability.

In effect, an ATC problem only occurs when the *relative separation* between aircraft is below a defined minimum. Accordingly, perturbations only have to be accounted for if they tend to result in a loss of separation. For instance in the simple example of Figure 15, this is not the case if the wind vector differs from the predicted wind. The trajectory prediction and control techniques proposed for DMA application are based on the *relative* separation between aircraft and consequently are more flexible as the "time" constraint in the clearance generation is essentially ground based and is not communicated to the aircraft. Therefore, *the full control potential of the operational flight envelope of the aircraft remains available for global optimisation.*

The distributed ATM system approach introduces an additional constraint in the form of "*absolute time*" which is in principle foreign to the basic air traffic control problem. In general, the more constraints which have to be considered in finding a solution the lower the change is, that the solution found is the optimum one. Therefore, although the 4D clearance approach has the potential to lead to a more stable environment (analogous to the railway system), *it remains to be demonstrated that the general application of 4D clearances in dense traffic conditions offers sufficient advantages in terms of ATC capacity and direct flight operating costs over the simple ground based approach,* especially when considering the high cost of its implementation and maintenance.

### 13.9. The speed control issue

"Closed loop" trajectory prediction systems, whether airborne (4D-FMCS) or ground based (CINTIA), require the control of certain flight parameters to meet the target constraints. The use of a variation of airspeed to lose or gain transit time may be an obvious choice at first sight, but the applicability has been a contentious issue in many discussions. What is the factual situation? For a modern twin jet Figure 16 depicts the operational range of True Air Speed (TAS) versus altitude. The speed range is presented for a high and an average aircraft mass. The higher end of the range is limited by the so called Vmo and Mmo values which are related to the structural limitations defined by the aircraft manufacturer. At the lower end of the range, at lower altitudes, the minimum drag speed is a practical limit and low speed buffet at the higher altitudes. These speeds depend on the aircraft mass. For flight economy, the optimum cruise level is close to the maximum possible. The diagram clearly indicates that at high altitudes the range available for speed control is indeed very small.

Before drawing conclusions too hastily let us consider at the fuel burn characteristics. Figure 17 shows the fuel burn in horizontal flight versus cruise level. The curve which corresponds to the left vertical axis presents the kilograms of fuel required to fly one nautical mile on the "long range cruise speed" schedule recommended for the particular altitude. Indeed, the higher the cruise level, the less fuel is required to travel a given distance.

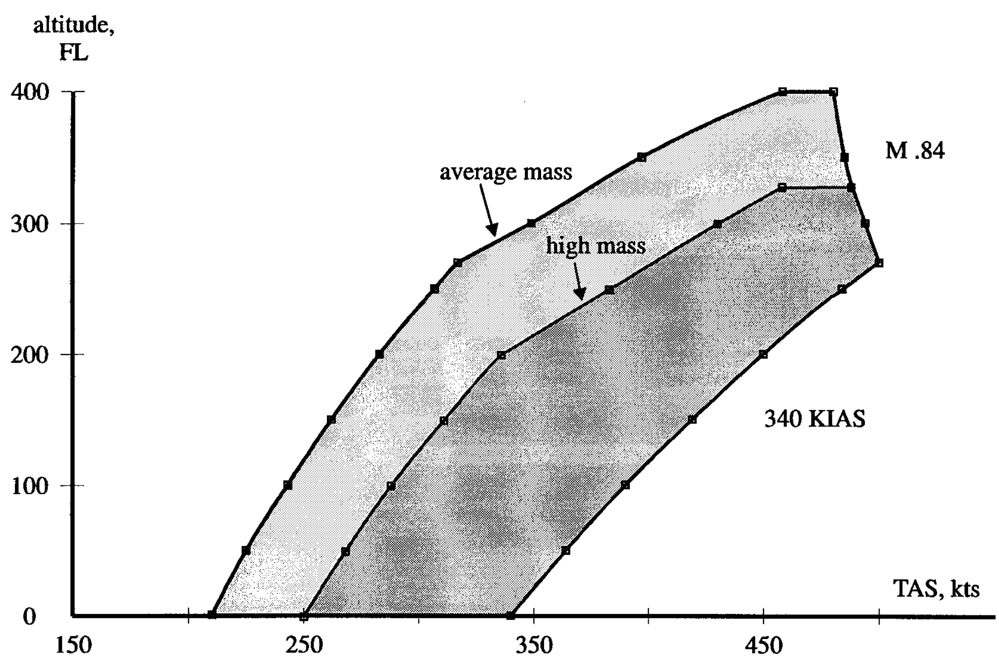



Figure 16 Operational speed envelope of a modern twin jet transport aircraft

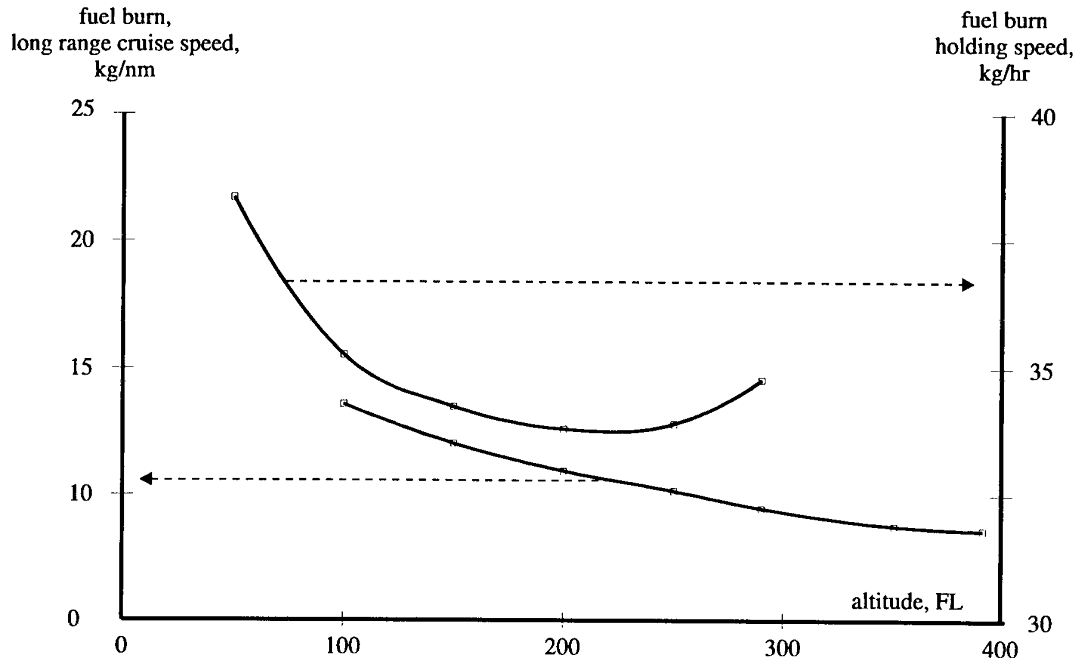


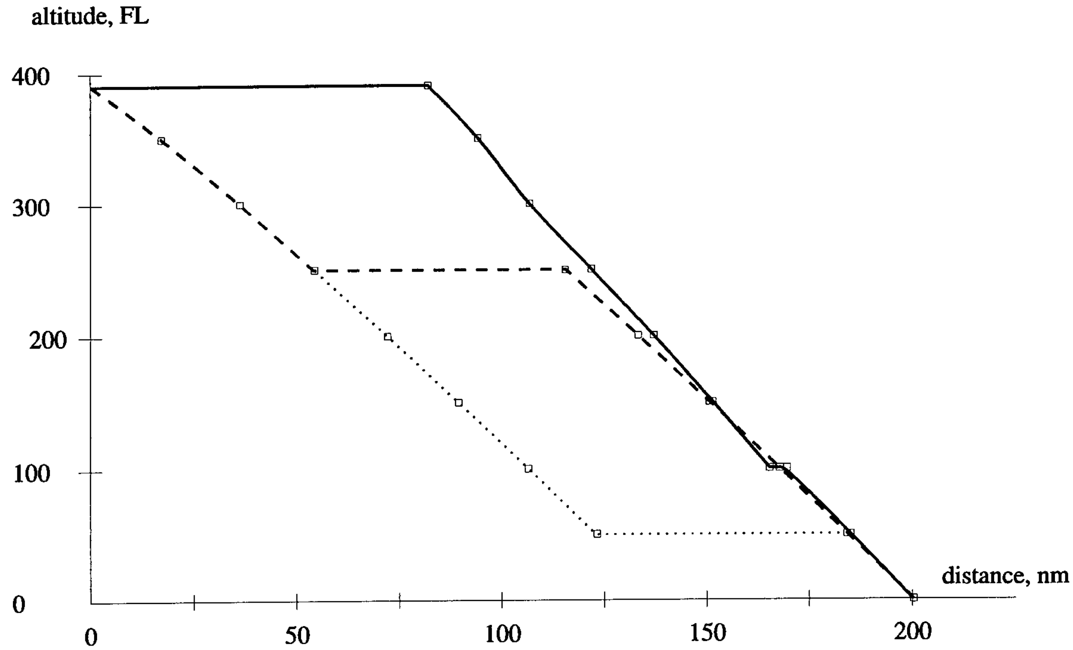

Figure 17 Total fuel burn of a modern twin jet in different phases of flight.

However this is only one part of the story. For the aircraft operator the optimum flight profile is the profile that results in overall minimum cost, viz. the sum of time and fuel costs. Consequently, if the transit time is defined, the minimum cost profile for the aircraft operator is *the transit procedure that meets the constrained flight time at minimum fuel burn.* Therefore it is also of interest to investigate the fuel flow per unit of time. The curve corresponding to the vertical axis on the right side of Figure 17 shows the fuel burn in kg/hour for the same aircraft cruising at the recommended holding speed. It appears that the minimum fuel burn per unit of time is achieved between FL 200 and FL 250. This is typical for many commercial jet aircraft.

### 13.9.1. How to loose time?

In Figure 18-a,b the results are summarised for two case studies related to a cruise-descent section of flight with a total extent of 200 nm. For each case three transit scenarios are investigated with different cruise levels and speed profiles. The first case assumes unconstrained flight: the aircraft is the only one in the sky and therefore not hindered by any other traffic. The first scenario, represented by the solid black line, pertains to a flight at optimum cruise level of FL 390 and speed M .81, followed by the standard descent M .78/300/250 KIAS. The flight from entry until touch down takes 30 minutes and 1038 kg of fuel. In the second scenario, at entry the aircraft descents to FL 250 and continues to proceed at the lowest possible speed within the operational speed range of the aircraft. The transit now takes 40 minutes and uses 1083 kg of fuel. In a third, hypothetical, scenario the aircraft proceeds again at the lowest possible speed profile but now descends immediately after entry to FL 50. The transit time has increased to 44 minutes and 1426 kg of fuel has been burnt. From these data it can be concluded that under such traffic conditions, the first transit procedure (solid black line) is by far the most economical, i.e., minimum transit time and at the same time minimum fuel burn. However, note that by descending the aircraft before the optimum top of descent, speed control could provide a possible range of transit times of 14 minutes.

For the second case study it is assumed that the aircraft can only be accommodated at the traffic convergence point 45 minutes after entry in the area considered. The basic flight extent remains unchanged and holding will be effected at FL 50. The results for this case are summarised in the Figure 18-c. It is clear that the most economical scenario is now the second one where the aircraft descents to FL 250 immediately after entry into the control area. Now the most economical scenario of the unconstrained case 40% more fuel is now burned at the same transit time. The advantages in terms of direct operating cost for the airlines are obvious. In this case technically, a descent to FL 50 could even be considered, if it would simplify the overall traffic situation as the increase in cost is only minor.




(a) Different transit procedures

flight distance : 200 nm — no time constraint

| | cruise phase | | | | descent phase | | | total | |
|---|---|---|---|---|---|---|---|---|---|
| | level (FL) | speed (M/KIAS) | fuel (kg) | time (min) | speed (M/KIAS) | fuel (kg) | time (min) | fuel (kg) | time (min) |
| ———— | 390 | .81 | 704 | 10.63 | .78/300/250 | 334 | 19.74 | **1038** | **30.37** |
| - - - - - | 250 | 210 | 634 | 11.22 | .78/240/210 | 449 | 29.06 | **1083** | **40.28** |
| ............ | 50 | 210 | 977 | 15.36 | .78/240/210 | 449 | 29.06 | **1426** | **44.42** |

(b) Transit time unconstrained

flight distance : 200 nm — transit time : 45 min

| | en route part | | | hold at FL 50 | | total |
|---|---|---|---|---|---|---|
| | level (FL) | time (min) | fuel (kg) | time (min) | fuel (kg) | fuel (kg) |
| ———— | 390 | 30.37 | 1038 | 14.63 | 935 | **1973** |
| - - - - - | 250 | 40.28 | 1083 | 4.72 | 302 | **1385** |
| ............ | 50 | 44.42 | 1426 | 0.58 | 37 | **1463** |

(c) Transit time constrained

Figure 18 Transit time and fuel for a 200 nm flight leg.

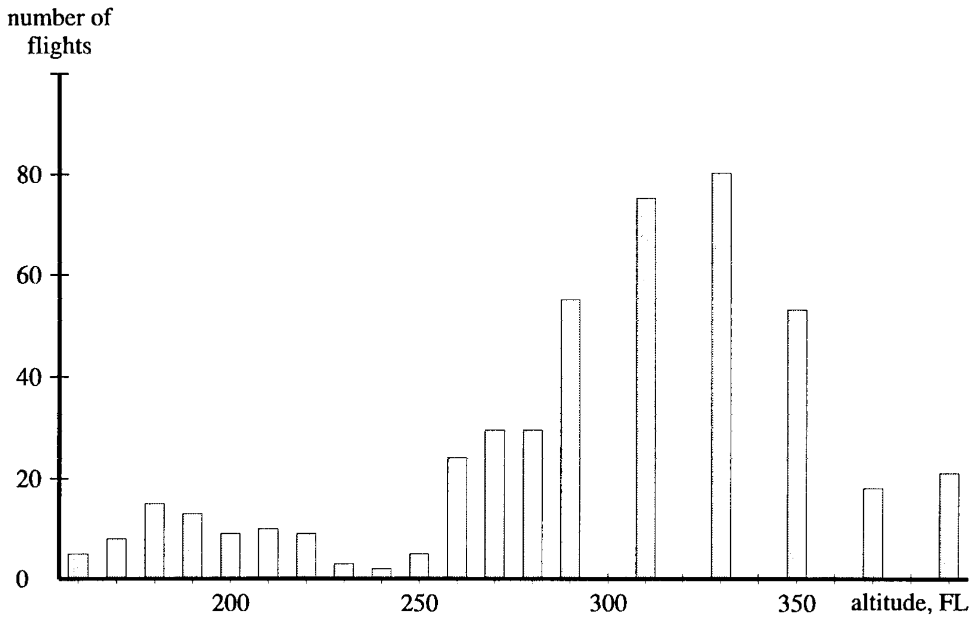



Figure 19 Typical distribution of flight level occupancy at an enroute waypoint

**13.9.2. How to gain time?**

If our subject aircraft is the first one in a queue it is of interest to advance its arrival time at the traffic convergence point as much as possible to make maximum use of the available capacity. Although the advancement of the first aircraft could lead to a cost penalty for that aircraft, globally an overall cost reduction could result, as all succeeding aircraft would be delayed less.

Let us consider the same environment as depicted in Figure 18., i.e., a cruise-descent sector with an extent of 200 nm. From the operational speed envelope presented in Figure 16 it can be deduced that maximum TAS is obtained around FL 270. The scenario for minimum transit would be "descent at entry to FL 270, cruise at M .84 and then descent at 340 KIAS". The minimum transit time obtained is 28.37 min. This is two minutes less than the transit time of the optimum flight profile. However the fuel required to be so fast is 1456 kg and this is 418 kg or 40% more than on the optimum profile.

In conclusion, it is possible to gain flight time even in a relatively small area, but the gain is limited and can only be obtained at relatively high fuel cost. Global optimisation strategies should carefully select the "number one" flight in the sequence in order to achieve an overall benefit.

**13.9.3. Can speed control be implemented?**

En route speed control can offer considerable savings in aircraft operating cost, but can it be implemented? Let us have a look at Figure 19 which presents a histogram of flight levels assigned by ATC for a typical en route reporting point in Europe. The highest traffic density is observed at the levels 290 - 350. As discussed above, enroute speed control is most efficient at cruise levels below FL 270. Figure 19 shows that at precisely those levels ample capacity is available. Consequent application of the control technique through *efficient multi sector planning will result in a capacity increase through a more balanced use of available flight levels and at the same time provide a considerable reduction of direct aircraft operating cost.*

However, on the other hand, general application of speed control will considerably increase the range of air speeds occurring at the same time in a given airspace. This could complicate the traffic situation seriously as overtaking aircraft require a lot of attention from the controllers. It is expected that *adequate working rules and procedures would need to be established* to make full use of the technical capabilities of the aircraft.

When the geographical area over which speed control can be exercised becomes larger, the required deviation from the aircraft's optimum flight profile will decrease to meet a time constraint. Therefore *the planning of traffic flows over more than one sector is the indicative way to go.* The advisories generated by multi-sector planning tools, e.g., an Arrivals Manager are communicated to the controllers in the form of "Best Next Clearances".

## 14. USING THE *"BEST NEXT CLEARANCE"*

Typical examples of how the concept of "Best Next Clearance" might be integrated in a modern HMI design are shown in Figure 20. Three aircraft are inbound to the TMA. The standard radar identification label consists of two alphanumeric data lines. The first line includes the callsign (BAW384), the weight category (i.e. "H" for Heavy, "M" for Medium and "L" for Light) and the sequence number (3) at the hand-over point from the ACC sector to the TMA. The second line shows the current flight level (167) as received through Mode C, the flight level to which the aircraft is cleared by the controller (100) and the ground speed in tens of knots (36) as extracted from the observed radar track.

If relevant, the DMA advisories are displayed in the extra line of the radar label normally reserved for emergency identification. The "1de" message for KLM832 warns the controller that within 1 minute, the aircraft will reach its optimum top of descent point to achieve the planned hand-over altitude. The "/28" message for DLH278 tells the controller that, if the indicated airspeed of this aircraft is now reduced to 280 knots IAS, minimum separation will be ensured at the handover point with respect to KLM832. Note that, when the traffic flow evolves as planned, the third line of the radar labels is empty and the information content of the radar screen will be equivalent to that of an ATC system without such an aid.

Clearly, with the generation of *"clearance advisories"*, one is entering dangerous territory. In principle any advice given will, to a certain extent, tend to limit the mental freedom of the controller to make his own decision, if only by inurement. However, it is a prerequisite to obtain the above mentioned potential improvements in efficiency of controller teams. So how should such DMA clearance advice be interpreted?

Assume the situation where the DMA tool has concluded that, if the present trend continues, two aircraft in the next ATC sector have a potential loss of separation over a convergence point, and, also assume that the problem can be easily solved by reducing the speed of one of the aircraft. The control team currently in charge of the subject aircraft will receive the speed advice from the DMA tool. As the information is not associated with an imminent problem in their own sector, they will deal with it at an appropriate moment. The advised speed is lower than the current aircraft speed and therefore the message conveyed tells the control team, that in effect, time must be lost.

They now have several options :

- the easiest is simply to ignore the advice and to leave the solution of the problem to their colleagues in the next sector where the problem has been detected ;
- to ask the aircrew to adjust the aircraft speed to the one suggested by the DMA advice ;
- to decide to vector the aircraft off-route until the advised speed matches current aircraft speed ; or,
- to descend the aircraft in order to obtain a lower ground speed.

In effect, the "best next clearance" tells the controller that if the flight profile of the aircraft is not modified, loss of separation with another aircraft will occur at some instant in the future. It provides him with an indication of the extent of the required modification in the form of a *"possible solution"*. Given this freedom of decision of the controller it is essential that "best next clearance" is regularly re-assessed and updated, preferably every time new position data are received by the ATC data processing system. This is a key element in the control loop of a "closed loop" trajectory prediction system.

### 14.1. Compatibility with data-link applications

The assessment of the Best Next Clearance approach was part of an exercise jointly conducted with the UK-CAA demonstrating the capabilities of a mode-S data link in a realistic ATC environment (Reference 22). In a simulated ACC sector, the ZOC Arrival Manager advised the controller how to achieve optimum hand-over conditions to the TMA sector. The generated "best next clearances" were prepared such that they could be transmitted directly via the data link to the BAC 1-11 research aircraft of DRA-Bedford. This "real" aircraft was integrated within a stream of simulated aircraft to provide the controller with a realistic traffic sample. On the radar screen the Best Next Clearances were communicated to the controller through an additional line of the aircraft identification label.

The use of the data link led to a considerable reduction of the controller workload. Integration of the Best Next Clearance into the radar label proved to be efficient, as the controller could now search for new information on the basis of the shape of the label rather than of its alphanumeric contents. Further important conclusions of this experiment were that the ZOC Arrivals Manager and the way in which it was implemented were fully compatible with an ATC data link environment. In addition, as the data processing for the Decision Making Aids is completely ground based, the traffic mix of data link and non data linked equipped aircraft did not degrade the overall performance of the ATC system.

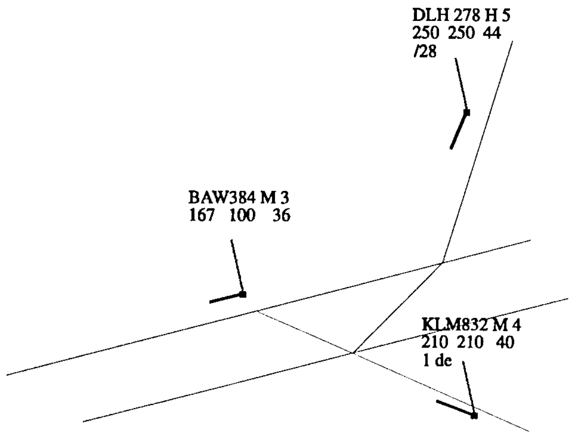



Figure 20 Display of "Best Next Clearance" in radar label

## 15. THE DETECTION OF POTENTIAL CONFLICTS

Today, automated conflict detection functions already support the air traffic controller at several levels. The Short Term Conflict Alert (STCA) function is the most widely implemented. It is a "safety net" that automatically monitors the evolution of the traffic and warns the executive controllers for potential conflicts. For this application the Future Situation Data is generated by an "open loop" trajectory prediction module based on the extrapolation of the observed radar speed vector. The expected accuracy of the predicted trajectory limits the effective time horizon of the STCA to the order of two minutes.

A second application is the Medium Term Conflict Alert (MTCA) function which supports the work of the planning controller. This function is gaining importance rapidly where flight progress strips on paper are being replaced by electronic media. Again an "open loop" trajectory prediction function establishes the Future Situation Data with a target time horizon of about 20 minutes. The subsequent conflict search is executed with procedural separation criteria. In general these are considerably greater than the minimum radar separation criteria and typically are of the order of 5 minutes of flight or 15 nm. When a potential conflict is detected, the planning controller may update the plan to find a conflict free clearance or mark the flight for special attention. Subsequently it is left to the executive controller to monitor the flight closely and, if there is a real risk that the conflict might materialise, to solve it through tactical clearances. The executive controller can only monitor a limited number of potential conflict situations. Consequently the ATC capacity achieved depends to a large extent on the efficiency with which potential conflicts can be avoided at the planning stage.

### 15.1. The technique of conflict detection

When a large number of aircraft have to be considered in a search for potential conflicts the required processing can soon become exorbitant. A "cascade" data processing strategy is required which intelligently reduces the total amount of processing through the application of data filters. First, "coarse" filters are applied to identify on the basis of planned route and absolute time whether a conflict search for a given pair of aircraft is required. The efficiency of these "coarse" filters to reduce the number of flights, or parts thereof, to be considered for the detailed conflict detection algorithm is of prime importance for its success. When two flights do have common parts a detailed comparison of the 4D flight profiles is required.

Different methods can be applied for the conflict search each with their own merits and disadvantages. Assume the case where the trajectory predictor produces (x,y,z) co-ordinates for normalised times (t). The conflict search then checks 3D volumes of protection. In another approach the trajectory predictor computes for the normalised positions (x,y), i.e. the waypoints along the route, the (t,z) window and this requires a 2D conflict search. It is clear that the latter is seems more efficient from a computational point of view, but it should not be forgotten that additional checks are required to detect overtaking traffic and for traffic in the close vicinity of convergence points. The actual technique selected is purely a technical issue and depends on many criteria.

### 15.2. Application in high density sectors

The "open loop" trajectory prediction with subsequent conflict detection is only applicable in an ATC environment where the traffic density is sufficiently low to accommodate the relatively large sizes of the Volumes of Protection around the predicted position. Today, in several en route sectors, traffic is already so dense that flight planning on the basis of procedural separation criteria is no longer possible and flights are managed on the basis of radar separations. Under such conditions the simple MTCA function described above, does not produce practical results.

By contrast "closed loop" trajectory prediction systems like CINTIA, do not suffer from these drawbacks as the separation required at the target convergence point can be defined as a constraint. A possible enroute application is the "*conflict monitor*" function. Its operation is best illustrated using Figure 15. Assume that aircraft 1 to 3 are flying at the same level. The controller can select automated assistance to monitor the separations between these aircraft. Through a few "clicks" on the HMI the controller can activate the

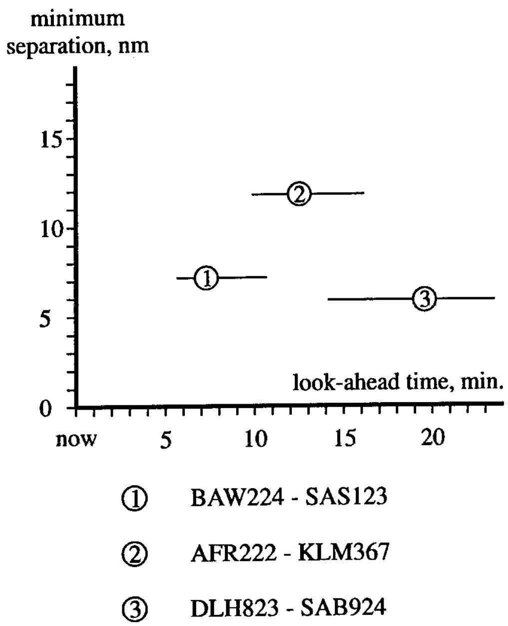



Figure 21 Conflict Risk Display

"conflict monitor" for the selected aircraft. This module establishes a "sequence" with aircraft number 1 as a "*moving target constraint*". Only if current aircraft progress would lead to a loss of separation, the "*conflict monitor*" would advise the controller about this fact through a Best Next Clearance advice that holds a possible solution. Such a mode of operation allows the controller at all times to define precisely for what problems and how much support he or she requires from the data processing system to prevent a possible overflow of information.

Alternatively, if aircraft 1 to 3 will not all maintain level flight in the area of interest, constraints can be proposed at convergence point C and subsequently monitored in a similar way.

In general the "conflict monitor" tool using a "closed loop" trajectory prediction system and the "Best Next Clearance" concept, allows the controller to select interactively any group of aircraft for which he or she would like to receive system support. The "separation trend" information discussed below, can assist to identify suitable clusters of aircraft.

Note that, with respect to the evaluation of the traffic situation at the convergence point, this approach does not require the processing step of conflict detection. However, this does not necessarily mean a reduction in computation complexity as probably several iterations of the trajectory predictor will be required to define the system plan that will meet the constraints. Moreover meeting the target constraints does not automatically imply that there will no be potential conflicts along the way. For this problem a trajectory prediction system that generates the 4D flight profile for normalised positions is an attractive choice. If, at a given waypoint an additional potential conflict is detected, the controller could obtain automatic assistance for the solution of the potential conflict by simply defining the target flight conditions at the waypoint and adding them to the constraints list of the subject flight or flights.

### 15.3. The Conflict Risk Display

Whatever techniques applied, the amount of information available inside the Flight Data Processing System is enormous and efficient filtering essential. One proposal to that effect is the "Conflict Risk Display" (CRD). When the conflict state of all aircraft in the sector is assessed, the CRD displays for every relevant potential conflict the characteristic data, i.e., time till conflict, minimum separation, duration, etc. Figure 21 illustrates how the conflict data were presented to the controller during the ODID IV simulation at the EUROCONTROL Experimental Centre, Bretigny, France in September 1993. To the left side of the window the callsign pairs are shown with conflict reference numbers. The graphic display on the right presents the predicted minimum distance of the conflict (nm) as a function of the look-ahead time (min.). The potential conflicts are represented by horizontal lines along the expected minimum distance. The left hand of the each line refers to the start of the potential conflict and the length of the line is a measure of its duration. As real-time progresses the conflict line will move from right to left.

Unfortunately, in particular the minimum separation distance information displayed has to be used very carefully as the position of the line does not reflect the uncertainty in the predicted flight profiles. In effect the accuracy of the displayed minimum separation distance will decrease rapidly with increasing look-ahead time as it is a function of the sum of the Volumes of Protection of the subject aircraft for a given reference time.

When a "closed loop" trajectory prediction system is applied to constitute the Future Situation Data the usefulness could decrease even further. Although in this case the accuracy of the prediction could be considerably better, the minimum separation distance is now also affected by the perturbations of the target constraints. These may not at all depend on the traffic involved in the specific conflict and, as a consequence, the minimum separation distance indicated might vary unexpectedly in unpredictable directions.

### 15.4. The "separation trend" information

A more elegant way to handle the uncertainty of the predicted future situation is to consider the "*separation trend*". When all flights are executed exactly in conformance with the assumptions taken for the trajectory calculations, the minimum separation distance at "now" time will materialise as predicted. However, as the progress of the flights is normally not in accordance with the predictions, the minimum separation will vary slowly with observation time. By "tracking" this variation, a "separation trend" vector can be established. Figure 22 shows the separation trend information in the form of the vertical lines in the CRD. The length of the trend vector results from the extrapolation of the observed trend from prediction time until now time. This means that, if the observed trend continues, the separation indicated by the end of the trend vector is an indication of the actual minimum separation that will occur when the "*prediction*" time has become the "*now*" time. The trend vector is terminated by an arrow indicating its observed evolution (second derivative).

For example, for conflict number 1 it is indicated that on the basis of the current system plan a potential violation of the minimum separation criteria may occur. However, from the observed evolution of the actual progress of the traffic it is deduced that the minimum separation is increasing. The evolution should be monitored carefully as the separation trend is itself decreasing as indicated by the arrow pointing downwards. By contrast, conflict number two refers to the case where, on the basis of the current system plans, the aircraft will not be in conflict, but it has been observed that the separation is decreasing rapidly and, accordingly, if the present trend continues, a potential conflict will develop. The display of the separation trend information will also confirm to the controller at an early stage if a corrective action has the desired effect on the conflict state.

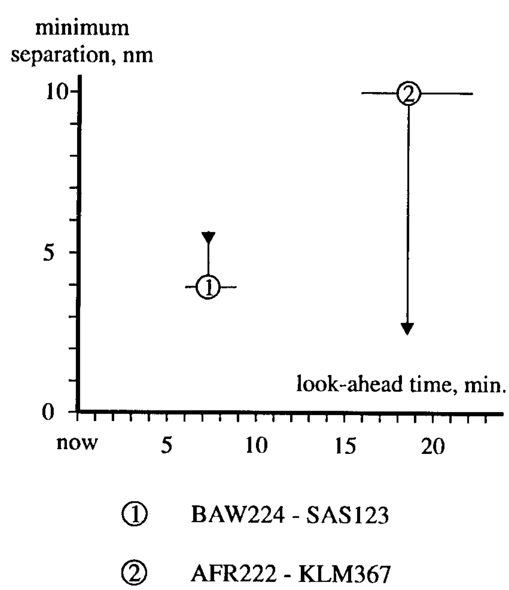



Figure 22 Display of "separation trend"

Separation trend analysis depicts the impact of the dynamic evolution of the traffic on the overall conflict state. Depending on route structure in a given sector, separation trend analysis can be produced in a general display window for all aircraft in the sector or in a dedicated window for specific crossing points.

The method is suitable for "open loop" trajectory prediction systems but at greater look-ahead times the trend vector may show rapid variations mainly depending on the phases of flight of the subject aircraft. In a "closed loop" prediction environment the stability of the target constraints directly affects the separation trend vector displayed. Again this problem can be eased by adding the potential conflict to the constraints list.

## 16. FLIGHT PATH MONITORING

Flight path monitoring can provide essential information to improve the quality of flight profile prediction. If the flight is performed according to agreed procedures, the observed track provides important information on the combined impact of the perturbations that affect the meteorological environment and aircraft performance (References 14 and 15). Subsequently this information can be used to improve the quality of the flight profile prediction for both "open" and "closed loop" methods.

*Conformance monitoring* is a system module that is part of many concepts for the next generation Flight Data Processing Systems. Its task is to check the actual progress of a flight against ATC clearances and/or the predicted trajectory. If the discrepancy is outside a given "*acceptance window*" the controller will be warned or the predicted trajectory recalculated.

There is no doubt that flight path monitoring to check the actual progress of an aircraft against ATC clearances for deviations of route, altitude, etc., is an additional safety net and therefore essential. However, when the concept of conformance monitoring is applied to control the re-prediction of the flight path, it should be noted that the sizes of the Volumes of Protection are increased with the dimensions of the "acceptance window". Inevitably the quality of the conflict state information is degraded. In contrast, if the latest available track information is fully used to improve the trajectory prediction process the resulting predicted flight path will comprise the maximum of information. This leads to the smallest Volumes of Protection and as

the start of the predicted flight path will, de facto, coincide with the observed aircraft position, conformance monitoring for the longitudinal flight component will not be possible.

## 17. EVOLUTION OF DMA APPLICATIONS

Decision making aids, as such, are not new to the ATC system. The obvious area of application is the management of arrival traffic in a Terminal Manoeuvring Area (TMA). Here the official minimum separation criteria at the convergence point (i.e. the touch down point at the runway) are well defined and the effectiveness of the tool can be evaluated relatively well. The evolution of these tools constitutes an interesting knowledge base essential for the design of current and future DMA applications.

### 17.1. "Fast-time" evaluations

At the end of the 70s a research project was started in EUROCONTROL which was aimed at reducing the fuel consumption and as a consequence, the flight operating cost in an extended TMA. The project became known under the acronym ZOC (Zone Of Convergence). The first step was to prove, in co-operation with research institutes, that the real-time, on-line scheduling of arrival traffic was compatible with the computing capacity available at that time (Reference 23).

In 1980 a "fast-time" study was started in co-operation with the UK-CAA to estimate the potential gain of an efficient arrivals management tool in an extended TMA (Reference 4). To that effect the radar tracks of all inbound flights to London Heathrow were recorded within the coverage of the London Radar (130 nm radius) and were subsequently used in different ATM scenarios. This study indicated that application of cruise/descent speed control as the prime parameter to control the arrival time could lead to a potential reduction of 22% in fuel consumption. At the time this represented a potential savings which was of the same order of magnitude as the enroute charges the airlines had to pay for the transit through the zone. In addition it was observed that the number of potential conflicts detected was reduced by 66% and that the average duration time of the remaining conflicts showed a reduction of 80%.

These results constituted the basis on which to proceed in 1982, with a large scale, real-time simulation of what we now consider to be the *"first generation"* of arrivals management systems.

### 17.2. First generation of arrival management systems

For a given traffic sample the system computed an optimum arrival sequence based on the preferred flight profiles as defined by the operators. This sequence was reconsidered every time a new aircraft entered the extended TMA. It was left to the control team to adapt the actual traffic so that the pre-calculated optimum sequence would be achieved. To that effect the controllers were provided with a *"Landing Interval Display"* presented on a separate display next to their radar screen. As shown in Figure 23, the Landing Interval Display presented in a graphical form the relative positions of the individual aircraft in the landing sequence and their predicted separations at touch down (Reference 24). Similar human-machine interfaces have later been adopted by the German COMPAS (Reference 25) and French MAESTRO (Reference 26) systems.

The simulation exercise confirmed that the planning of the arrival sequence already in the enroute part of the flight resulted in an overall smoother flow of traffic and could help, to a certain extent, the co-ordination between enroute and terminal area sectors. However, no increase in landing capacity could be observed nor could a significant reduction in flight operating cost be identified as was suggested by the earlier off-line study.

On the contrary, the simulation indicated that on-line, real-time, human decision making was superior to that available from the machine at the time.

### 17.3. Second generation of arrival management systems

In the second generation of arrivals management systems a symbiosis is sought between the capabilities of the human, in respect to decision making, and the computing power of the machine. A new strategy was developed whereby the machine proposes a plan which it considers to be optimal and will advise the control team on how to achieve it. But now, in contrast to the first generation tools, the machine will automatically update this plan in accordance with the actual observed evolution of the traffic, including the associated clearance advisories. In effect, every time new radar data becomes available, the plan is re-assessed and updated, if required. The "best next clearances" are updated on the basis of the latest actual traffic situation.

In an on-line implementation it is essential that the optimisation strategy is dynamically adapted to the actual traffic situation. It may vary from the *minimum flight cost criterion* under relatively low traffic demand to *minimum controller work load* in high traffic demand

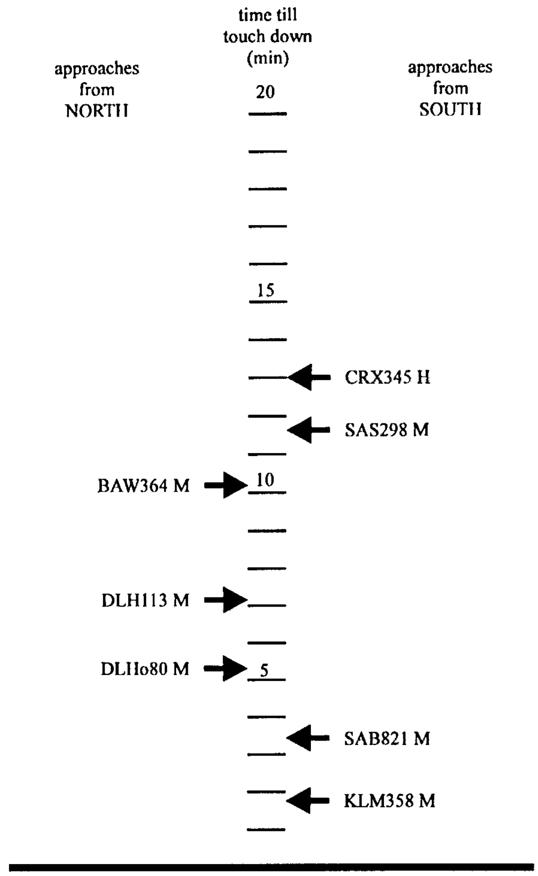



Figure 23 "Landing Interval Display"

conditions. This approach leads to a highly dynamic system that adapts itself to all controller decisions, external perturbations and traffic demand. The extent of the area considered ensures an efficient integration of enroute and terminal area air traffic management.

The above system description relates to the current implementation of the CINTIA trajectory prediction and control techniques in the Zone of Convergence (ZOC) arrival management system (Reference 20). Several of the above characteristics can also be traced in the CTAS arrival management system under development by NASA (Reference 27).

The work on ZOC constituted the basis for the definition of the multi-sector planning functions and data processing techniques covered by the Operational Concept defined for the design of Decision Making Aids. In the same context in Finland, the FCAA has commissioned under the ATM Integration (FATMI) programme a complete new ATC infrastructure for the whole of Finland. It includes the ASMAP (Approach Sequencing and Metering and Advisory Processing) Arrival Management function which is based on the ZOC concept. It will support, in an integrated way, the enroute control centre in Tampere as well as the terminal area control in Helsinki (Reference 28).

## 18. VALIDATION PROGRAMME

The research, design and implementation programme for advanced decision making aids requires a development and test environment, which will permit *on-going* evaluation of the concept design and operational validity. Previous experience with complex real time simulations and their extensive demands has proven that a considerable, dedicated effort is required.

It is important to recognise that the different system functions will be developed through an appropriate co-ordination structure, representing an internationally specified and agreed process. At various stages of its lifetime the validation environment will:

- provide feedback to the design process,
- form the basis for operational evaluation and performance tests, through real time simulation,
- provide a demonstration of functionality,
- provide a platform for evaluation through linking into live data at an agreed ATC Unit (or Units),
- provide a platform for the definition of future requirements.

In the design and validation process four stages can be identified.

During the early specification and design phases *static and dynamic mock-up's* of the system modules are required to study the basic HMI and system integration aspects, and, the impact on existing working rules and procedures. During this phase of the development, fast prototyping tools could be the appropriate vehicle.

A *research prototype* is required for the functional and performance evaluation. The functional evaluation will test whether the tool does what is expected. In the evaluation of the performance will assess whether the tool can accommodate the target traffic load. Note that the mock-up software is probably not usable for the research prototype.

Subsequently an *engineering prototype* will be built that answers the question whether the tool or function operates in the envisaged ATC context. In effect this includes the evaluation of the original concept.

The last step in the validation process comprises the development of an *operational prototype* that can

directly be integrated in an on-line ATC system. Typically when a module has reached this level of sophistication, it can be assessed in the test sector of the target ATC system.

The second and third steps of the above validation process require a dedicated simulation environment. The Simulation Facility for a Total Air Navigation System (STANS), which is described extensively in paper 9 of this AGARDograph, is an example of such a facility.

## 19. CONCLUSIONS

An operational concept is developed, based on Decision Making Aids (DMAs), to reduce the average controller workload per aircraft. DMA's enhance the ***task sharing*** between human controllers and the automated flight data processing system by providing controllers with better aids for decision making.

Two potential application areas are identified in which humans are less effective than machines, namely:

- the on-line planning of air traffic over an extended area, e.g., arrivals management, local flow control, etc, and,
- conflict monitoring.

As on the flight deck, the introduction of task sharing for decision making between humans and machines requires an efficient ***resource management*** for the now "extended controller team" in order to co-ordinate in time ***who*** does ***what, when*** and ***how***. From the safety point of view, special attention is needed for the ***"reversibility"*** aspects, meaning the possibility to revert to the pristine mode of non-automated functioning whenever needed. As for pilots, ***dedicated training programs and facilities become essential for controllers*** to maintain their skills in the case of degraded system support due to technical failures.

The quality of the human machine interface needs improvement. EUROCONTROL's ODID and the European Commission's SWIFT programmes lead the way.

The capability to predict the future flight paths of aircraft is an essential prerequisite for DMAs. The respective merits of two trajectory prediction methods, i.e. "***open***" and "***closed***" loop systems, are highlighted. Their suitability for use in specific DMAs is investigated.

Two practical implementation strategies are discussed in terms of ATC efficiency and cost, namely:

- an entirely ***ground based ATM system*** in which the aircraft is only a potential source of information, and,
- a ***distributed ATM system*** based on a negotiated "contract" between the "***air***" and "***ground***" components for a conflict free flight path.

The ***ground based ATM*** system approach is compatible with the present infrastructure in the air as well as on the ground. It constitutes a symbiosis between human and machine capabilities and is based on available technology. It has been indicated, that ground based ATM offers very high promises in terms of cost/benefits ratio.

By contrast the ***distributed ATM*** system is faced with the very high cost for the required infrastructure. ***Certified 4D flight management systems*** are a prerequisite on-board all aircraft together with a ***high capacity air-ground data link network*** to support the negotiation process. It is still to be demonstrated, that in a practical environment in dense traffic situations, general application of 4D clearances will offer sufficient advantages in terms of ATC capacity at an acceptable cost for the users.

**The paper illustrates that we can do many things already NOW!** *The ATM world wants to see rapid practical achievements.* Decision Making Aids are one aspect of this development which can reach fruitful implementation before the turn of the century. And, who knows, if DMA's are efficient enough, they could even last much longer.

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# CHAPTER 7

## A LOOK FURTHER INTO THE FUTURE

# OPTIMISATION DE L'ENSEMBLE DES TRAJECTOIRES
## - deux phases du développement -

par

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## 1. INTRODUCTION

Lors de son allocution de bienvenue aux participants de la Conférence AGARD tenue en juin 1972 à Edimbourg (Ecosse) sur le contrôle de la circulation aérienne (désigné habituellement par l'acronyme ATC, Air Trafic Control), N. Coles, Directeur adjoint, "Establishments and Research" faisait la déclaration suivante : "... Au Royaume-Uni, il se pourrait que nous ayons un jour à faire face à certains des plus sérieux encombrements que connaît le continent américain. Toujours est-il que nous enregistrons parfois des temps de "stacking" égaux ou supérieurs aux temps de vol correspondants !" [Réf. 1]

En mai 1993, la Commission Guidage et Contrôle organise un symposium consacré au rôle que l'intelligence artificielle pourrait jouer dans la gestion du trafic. Dans le discours liminaire exposant le thème de la conférence, G. Maignan reprend cette citation, la développe, expose la complexité du contrôle aérien et trace les grandes lignes d'une automatisation globale [Réf. 2], dont un de ses collaborateurs présentera un projet allant dans ce sens au cours de la même réunion [Réf. 3].

Jusqu'à très récemment, les développeurs les mieux placés, voire les plus téméraires, ne prévoyaient point avant 15 ou 20 ans le remplacement du contrôleur humain par une combinaison de matériels/logiciels comme c'est le cas depuis plusieurs années déjà dans certains transports terrestres, tels les métros municipaux.

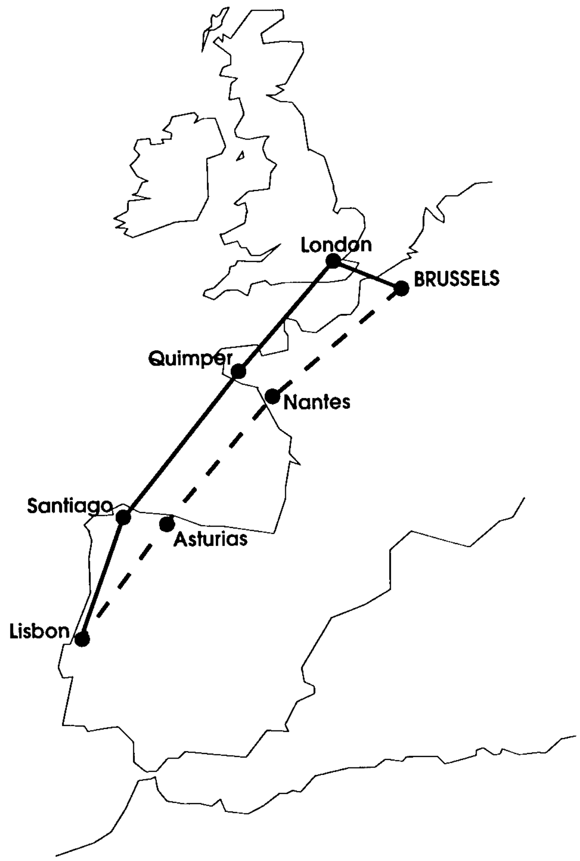
Aujourd'hui, qu'en est-il ? Des efforts considérables sont entrepris par l'ensemble des administrations concernées, mais il faudra sans doute attendre encore longtemps pour en ressentir les effets bénéfiques. Témoin, cette expérience récente vécue et confirmée par plusieurs autres du même genre. Au départ de Bruxelles, à destination de Lisbonne, tout s'annonce bien, l'avion décolle avec un retard sur l'horaire affiché de l'ordre de 5 à 10 minutes. Après quelque 40 minutes de vol, l'hôtesse invite les passagers à admirer la ville de Londres par les hublots de droite. Sommes-nous détournés ? Que non. A son initiative, le commandant de bord choisit cette route - particulièrement coûteuse pour la compagnie, nous confiera-t-il plus tard - plutôt que d'attendre pendant 80 (quatre-vingts) minutes, le créneau de décollage autorisé par le contrôle pour pouvoir suivre une route normale (Figure 1).

Ceci montre bien la disparité entre les limitations de capacité transmises par le gestionnaire des flux de trafic au contrôleur humain et le potentiel d'une gestion en-ligne dans laquelle les passages de chaque avion aux points critiques seraient contrôlés par ordinateur à quelques secondes près.

Aussi, entre la situation actuelle et le lointain futur où gestion en-ligne, guidage et pilotage fonctionneront en mode automatique, il y a place, nous semble-t-il, pour des systèmes de transition, compatibles avec les habitudes et techniques opérationnelles d'aujourd'hui, mais directement adaptables aux nouvelles technologies, telles les communications numériques automatiques, le positionnement via satellites et le pilotage optimisé par le gestionnaire de bord ou par le gestionnaire central de la compagnie couplé au gestionnaire de trafic basé au sol et très précis dans le continuum spatio-temporel.

## 2. GESTION MONOTERMINALE

C'est ainsi que nous désignerons la gestion du trafic suivant les principes et techniques de contrôle développés dans le projet **Zone de Convergence** - intégrant départs et survols aux arrivées -, en y associant les aides décisionnelles issues du projet correspondant (**"Decision Making Aids, DMA"**, voir Chapitre 6).




**Pour éviter un délai au décollage de 80 minutes le Commandant de bord choisit une alternative coûteuse**

**Figure 1**

L'étendue d'une telle zone dépendra de plusieurs éléments dont, en Europe, les frontières nationales constituent certes un facteur limitatif indéniable. Les développements réalisés à ce jour et les implantations déjà entreprises par diverses administrations (voir Chapitre 5) prouvent le bien fondé d'une telle approche, quelles que soient les limitations résultant de son caractère local actuel.

Bien qu'il nous fût offert de présenter les principes d'une gestion monoterminale à maintes reprises [Réfs. 4, 5, 6, 7], nous en rappellerons les caractères essentiels, mettant l'accent, espérons-nous, sur ces points particuliers qui pourraient constituer autant de sources d'ambiguïté, voire d'incompréhension, lors de nos échanges avec certains de nos collègues.

### 2.1 Conditions initiales

Pour les **arrivées du monde extérieur**, les conditions d'entrée dans la zone sont à la fois imposées et aléatoires dans un intervalle d'incertitude dépendant de la qualité du contrôle de la zone amont.

Par contre, pour les **vols à l'arrivée issus d'autres points de la zone**, de même que pour les départs, les conditions initiales font partie des variables de contrôle du gestionnaire de la zone.

Pour ces conditions initiales, imposées ou contrôlées, il y a lieu de déterminer la trajectoire optimale amenant l'avion au seuil de piste (vol à l'arrivée) ou à la sortie de la zone (départ ou survol), compte tenu de l'ensemble du trafic. Dans les paragraphes suivants, nous rappelons ce que nous entendons par trajectoires optimales et résumons la manière dont elles sont déterminées.

### 2.2 Allocation des trajectoires contraintes

Le choix d'une trajectoire destinée à réaliser au mieux une mission donnée, se fait en veillant à satisfaire de manière dite optimum le critère mesurant en quelque sorte la qualité de l'exécution de cette mission. En

aviation civile, le critère omniprésent, sous-jacent à tout autre - l'exprimant ou ne le citant pas explicitement - est la sécurité. La sécurité de chaque vol pris isolément, la sécurité de l'ensemble des vols traités globalement. Dès lors, lorsque nous évoquons le choix d'une trajectoire, autrement dit d'un ensemble de paramètres définissant la position tridimensionnelle de l'avion en fonction du temps, ce choix est fait à l'intérieur d'un domaine de sécurité, qu'il s'agisse des possibilités mêmes de l'avion considéré ou des manoeuvres d'évitement éventuelles résultant de la présence d'autres avions.

Le sous-critère - "sous" par rapport à la sécurité - que nous noterons désormais simplement critère, est en général d'ordre économique. Il combine à la fois le temps de transit - entre entrée dans la zone et seuil de piste - et la quantité de carburant requise par ce même transit. En l'absence de séjour en orbite - ce à quoi visent le concept ZOC et les concepts à objectifs similaires -, exprimé en quantité de carburant équivalente, $Q$, le coût de transit équivalent est donc de la forme

$$Q = F_{tr} + T_{tr}\ I$$

expression dans laquelle $F_{tr}$ représente la quantité de carburant requise, $T_{tr}$ le temps de transit et $I$ le rapport des coûts unitaires à savoir le coût moyen de l'unité de temps de vol rapporté au coût de l'unité de masse de carburant, autrement dit l'index de coût, exprimé dans des unités appropriées de masse/temps.

Ainsi, pour un avion donné, entrant dans la zone à une altitude déterminée, à une distance du seuil de piste connue, piloté conformément à un indice de coût suggéré par la compagnie aérienne, il existe un profil de vitesse et un seul minimisant le coût de transit équivalent (critère économique combinant consommation et temps de transit) pour un temps de transit donné, tel qu'illustré à la figure 2. Dans ce diagramme, les seuls points à considérer sont ceux de l'enveloppe, chaque point étant associé à un temps de transit contraint particulier, le point $m$ correspondant à un temps de transit libre, autrement dit au temps de transit préférentiel réalisé conformément au profil préférentiel de l'usager de l'espace. Chacun des points de cette enveloppe définit complètement pour le temps de transit correspondant, le profil de vitesse dans le plan vertical, à savoir $\{v_{cr}, v_{de}\}$.

Pour les temps de transit situés en deçà ou au delà de l'enveloppe utile $\{s, r\}$, les profils éventuellement retenus correspondront soit à une descente à vitesse minimum le long de $\{a, s\}$, soit à une croisière à vitesse maximum le long de $\{r, d\}$. Les figures 2 et 3 permettent de se faire une idée de la comparaison de profils correspondant à deux philosophies opérationnelles distinctes - pour une même marge de contrôle possible -, l'une à indice de coût particulier minimum, l'autre à consommation minimum. Les créneaux visés diffèrent sensiblement et, d'une manière générale, les créneaux alloués différeront tout autant. L'effet de l'indice de coût sur le choix du profil de vitesse est illustré à la figure 4. Cette illustration est complétée à la figure 5. Cette figure met en évidence l'impact sur la position du parçours préférentiel ($m$), non seulement de l'indice de coût mais encore de la distance à parcourir dans la zone.

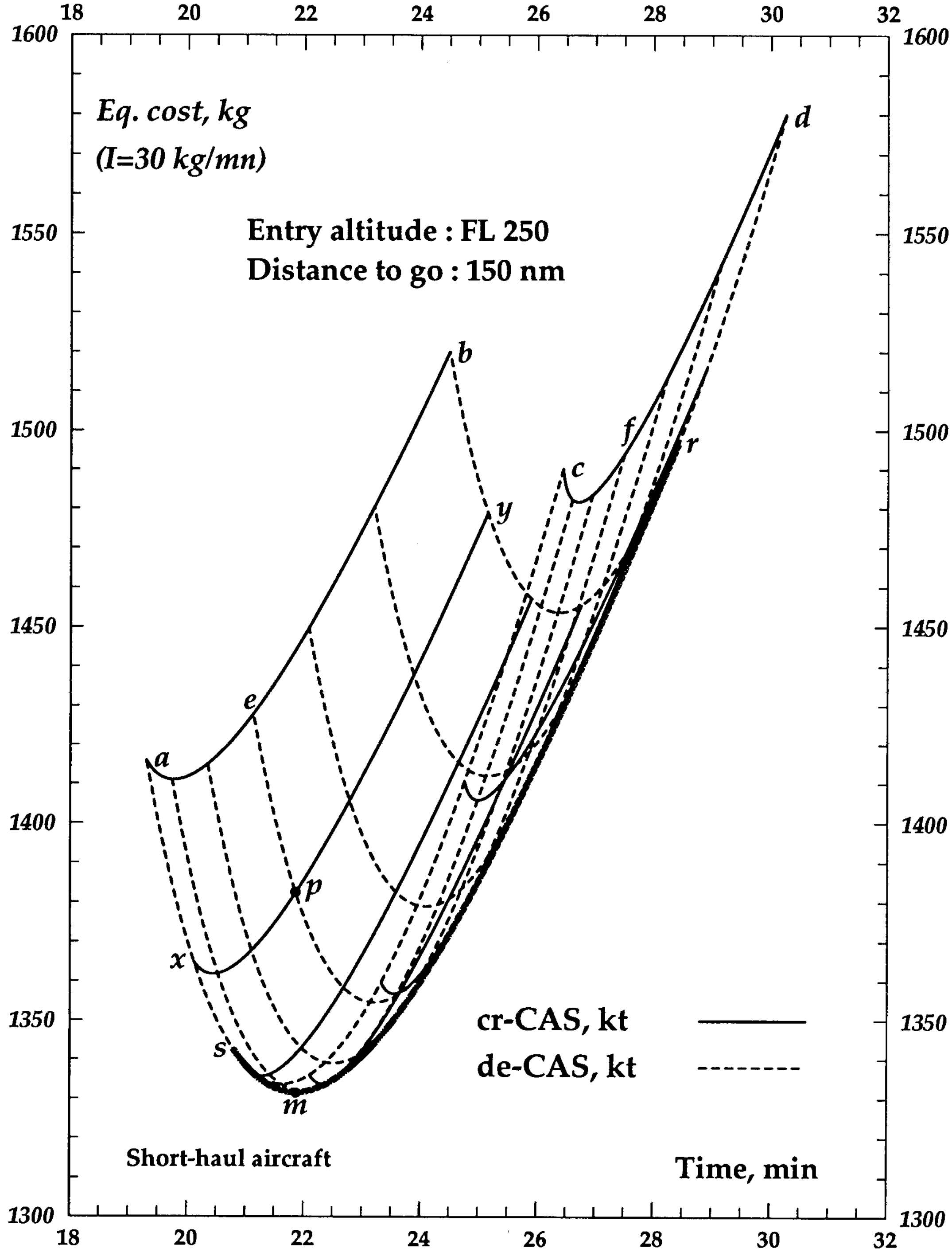
Rappelons qu'à chaque point de l'enveloppe - complétée par les intervalles $\{s, a\}$ et $\{r, d\}$ comme indiqué - correspond un profil $\{v_{cr}, v_{de}\}$ et par suite une distance et une durée de vol en croisière et en descente univoquement déterminées. La figure 6 montre, à titre d'exemple, les caractéristiques de descente réalisées pour un régime particulier des réacteurs, ici la descente est faite au régime de poussée résiduelle.

Nous avons présenté et discuté ces relations antérieurement [1980-82, Réfs. 4 et 8 à 15]. Les principes n'ont pas changé ; certes les expressions des consommations spécifiques se sont affinées suite, en particulier, à une excellente collaboration des compagnies aériennes. Désormais, nous pensons pouvoir dire que nous sommes à même, au sol, de définir les profils de vitesses relatifs à une trajectoire - temps de transit généralement contraint - avec une qualité comparable à celle qu'atteindrait le pilote assisté de son calculateur de gestion de vol.

### 2.3 Détermination des contraintes

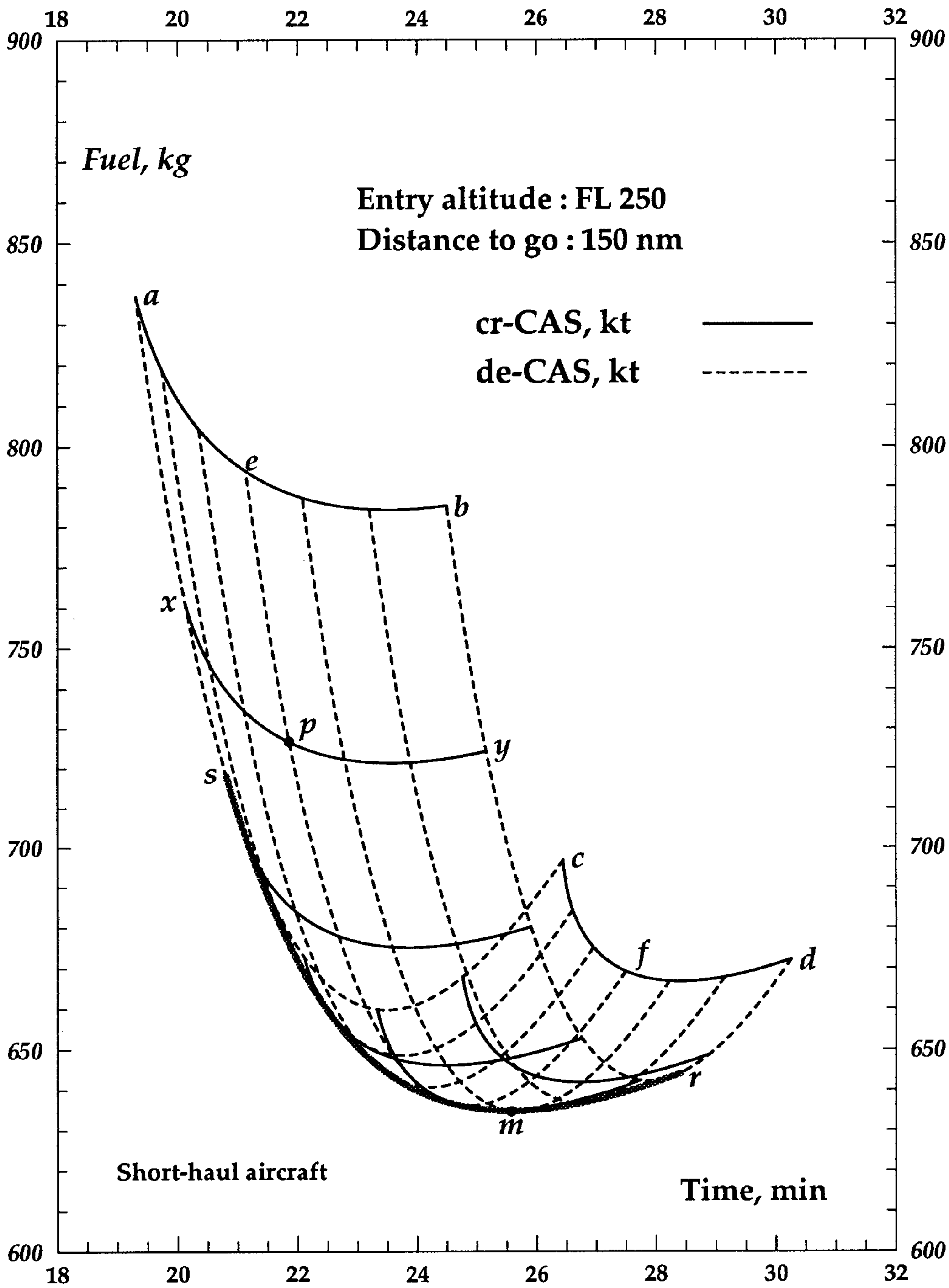
Lorsqu'un ou plusieurs avions entrent dans la zone, il s'agit de leur assigner des trajectoires - donc essentiellement de déterminer autant de profils de vitesse croisière/descente - aussi proches que possible du point $m$ correspondant au profil préférentiel, de telle sorte que la somme des coûts équivalents de l'ensemble des trajectoires concernées soit minimum. Différentes méthodes d'optimisation furent prônées voire essayées antérieurement, particulièrement les méthodes numériques de séparation et d'évaluation [Réf. 16], les techniques proposées par Odoni, Tobias, Dear, Trivizas et Bianco [Réf. 17] et bien d'autres encore, dont cette dernière référence fait une brillante synthèse. Plus récemment, certains auteurs préconisèrent la mise en oeuvre d'algorithmes génétiques [Réf. 18] bien que ceux-ci semblent peu adaptés - sous leurs formes actuelles - à la gestion en-ligne de problèmes tels que ceux qui nous concernent.

Il nous est apparu rapidement - en fait dès la première simulation en temps réel de la première génération du concept ZOC réalisée au Centre Expérimental en 1982 [Réf. 19] - qu'une stratégie combinatoire très simple n'impliquant généralement qu'un nombre restreint



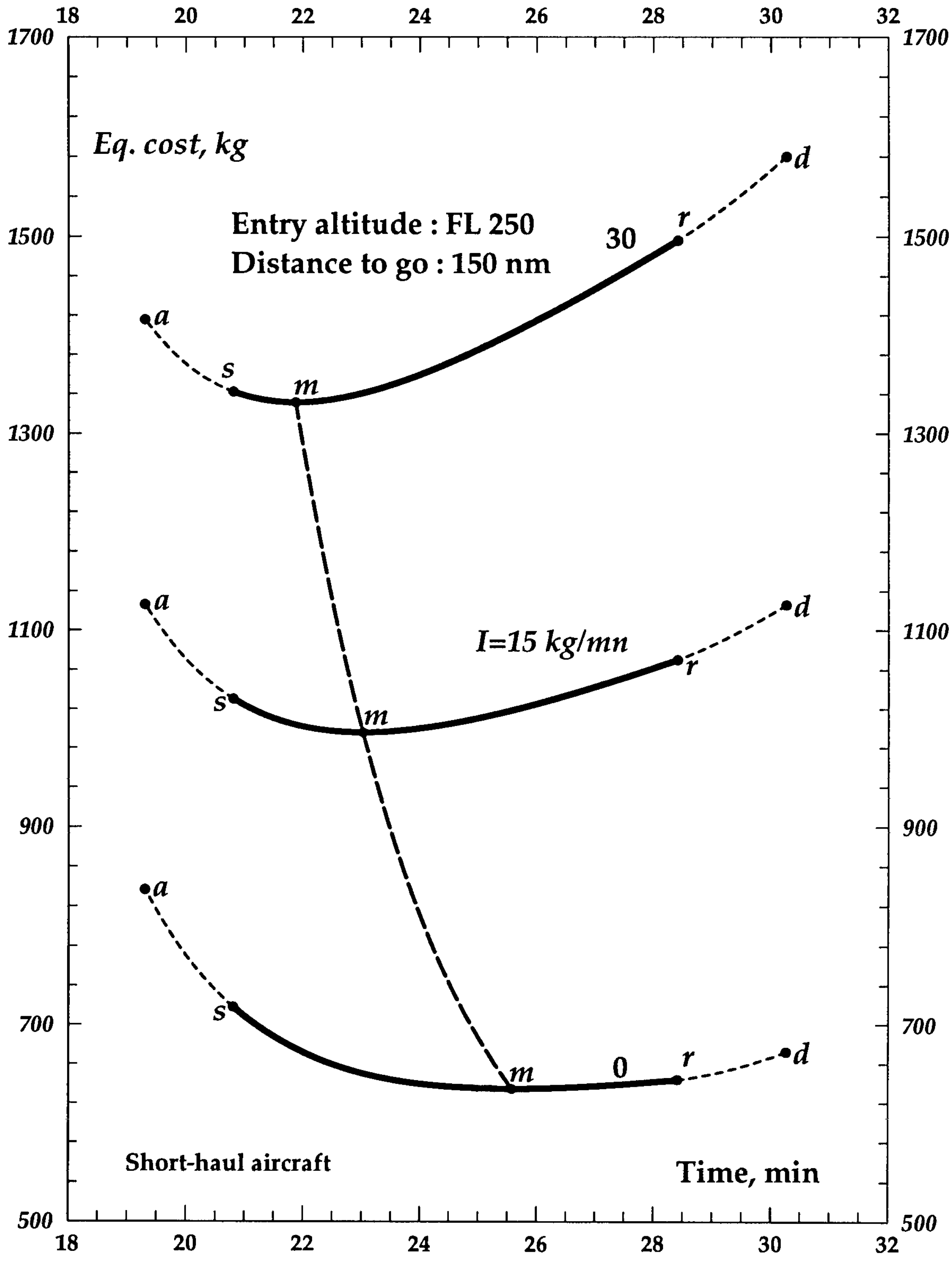

**Relation entre Profil de vitesse cr/de, Coût de transit équivalent et Temps de transit (L'enveloppe représente l'ensemble des profils utilisés)**

**Figure 2**



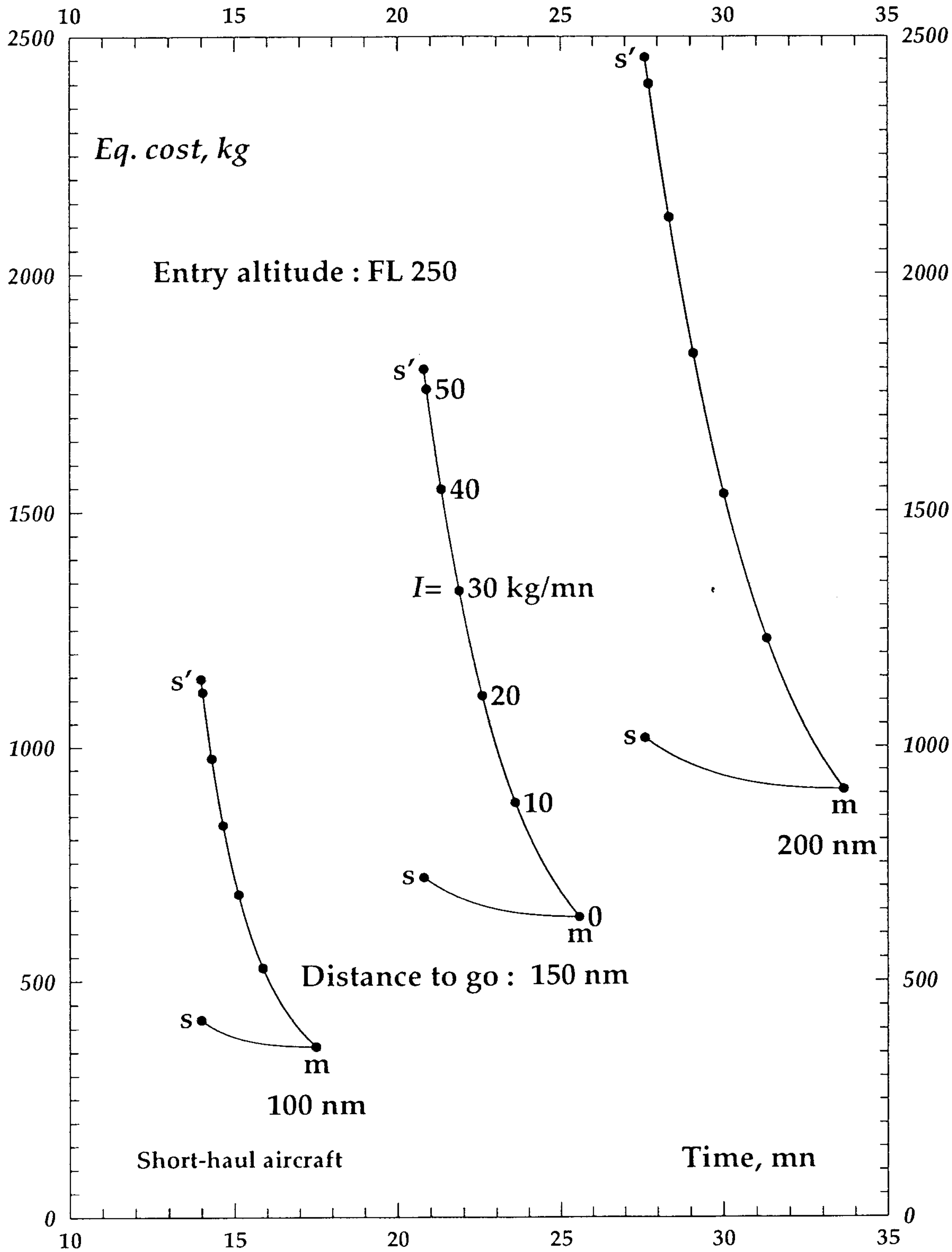

**Relation entre Profil de vitesse cr/de, Consommation de Carburant et Temps de transit**
**(L'enveloppe représente l'ensemble des profils utilisés)**

**Figure 3**



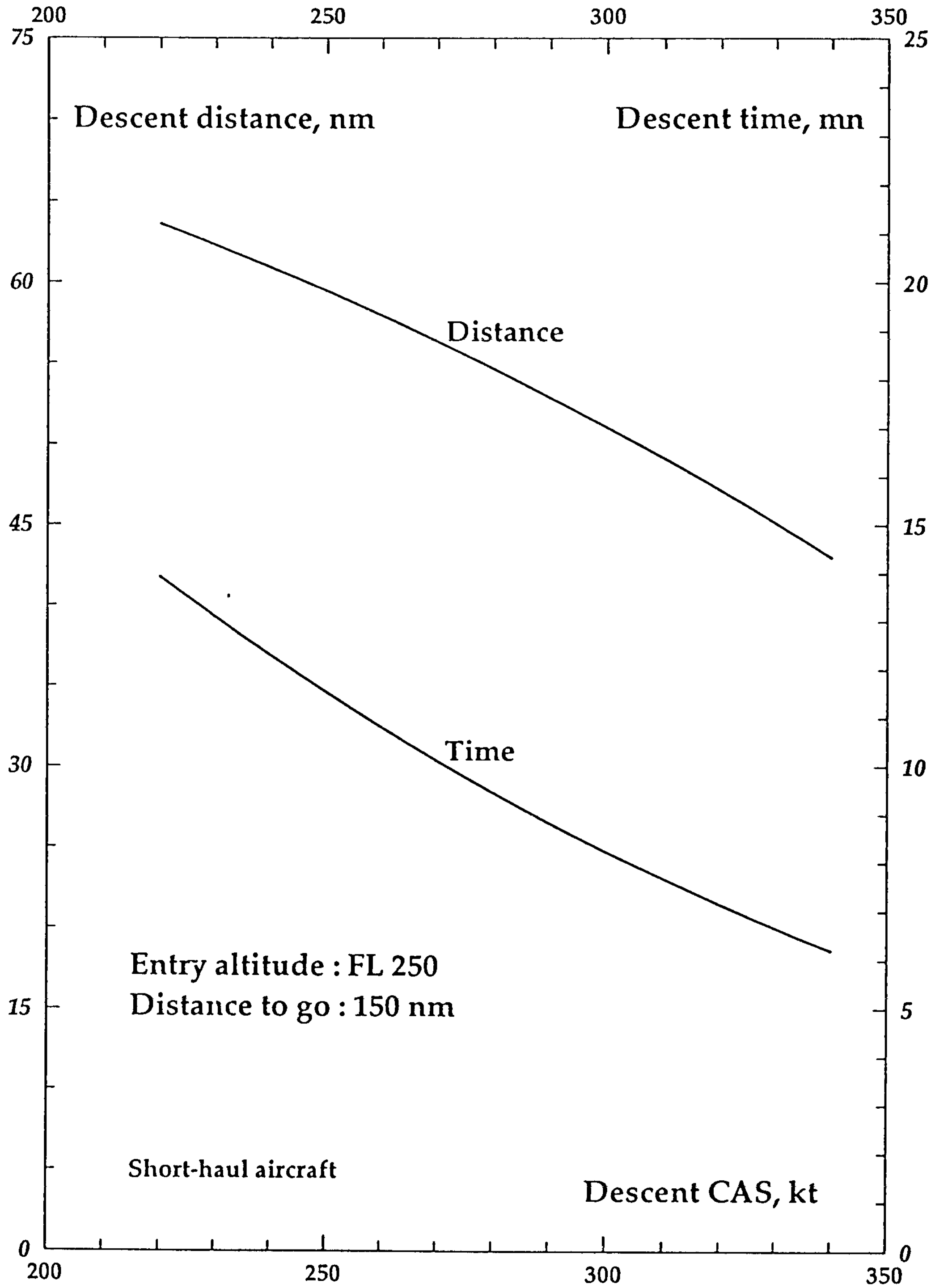

**Effet de l'indice de coût sur le choix du profil de vitesse**

**Figure 4**



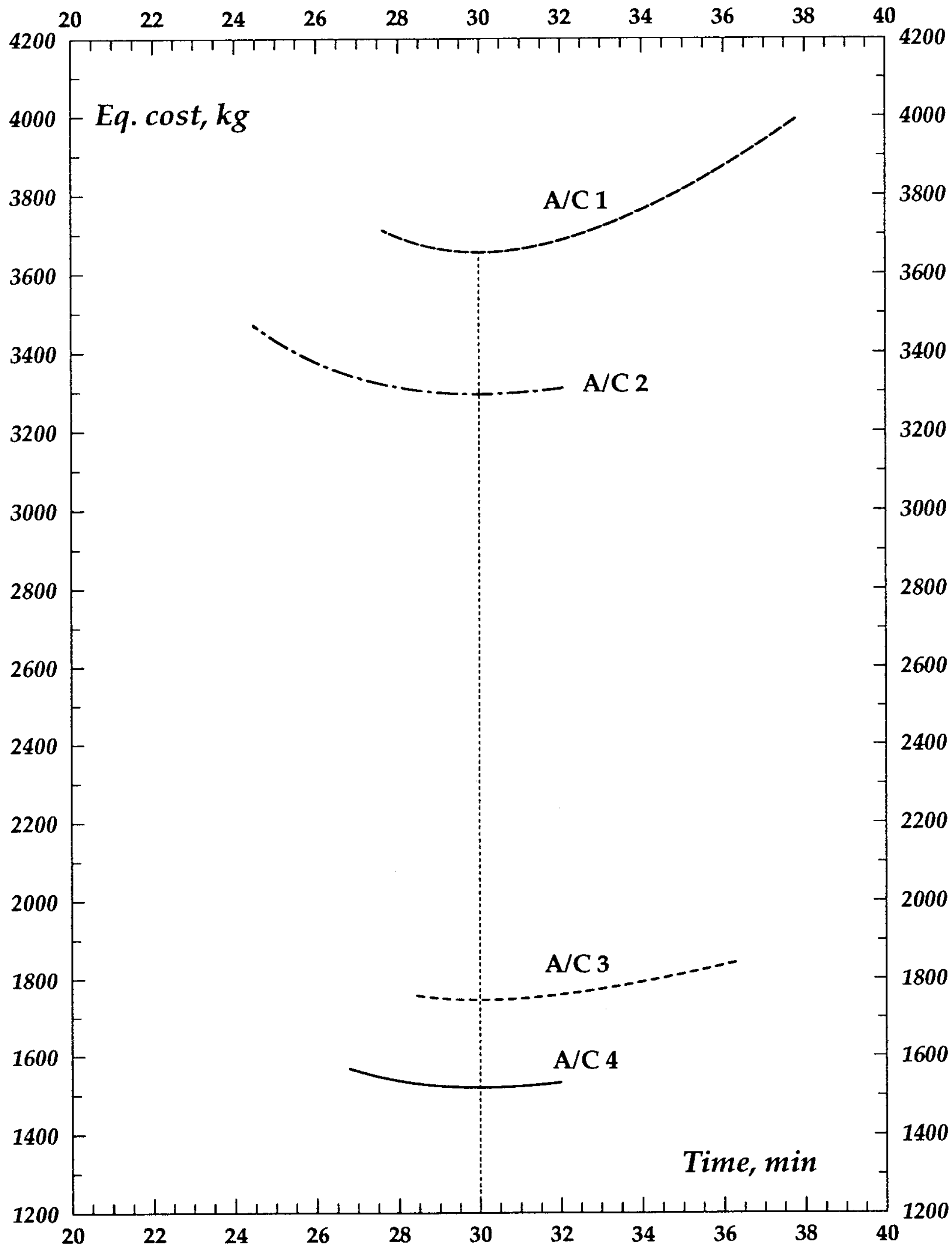

**Influence de l'indice de coût et de la distance à parcourir sur la position du profil préférentiel**

**Figure 5**




**Descente en régime de poussée résiduelle**
**- durée et distance de descente -**

**Figure 6**




**Plusieurs avions sont en compétition pour un même créneau**
**- ici 4 avions distincts, 2 long-courrier et 2 court/moyen-courrier -**

**Figure 7**

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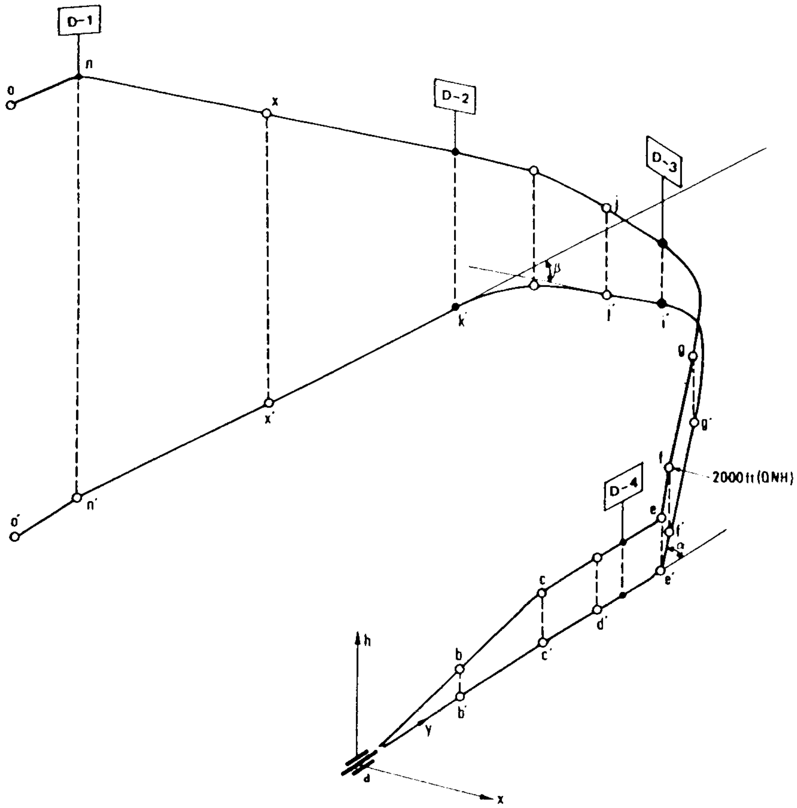
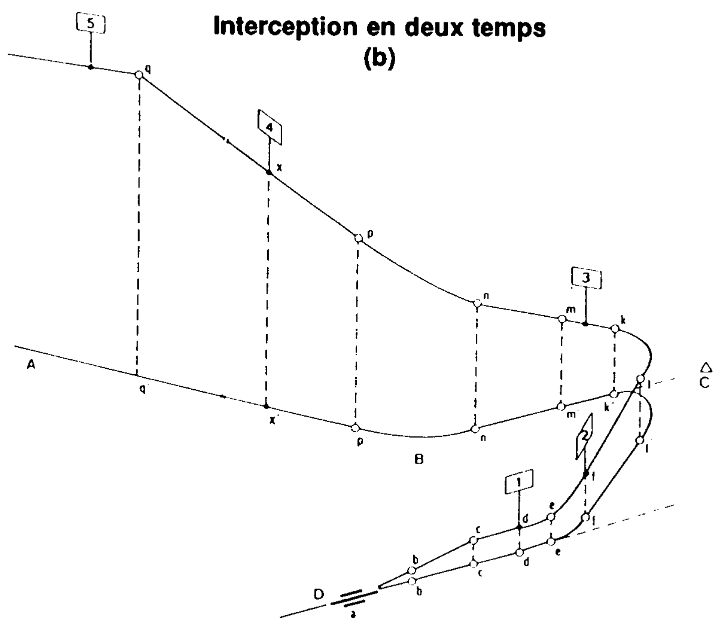
N.B. *Au cours d'un stage à l'Agence EUROCONTROL (août-septembre 1993) Eric Brasseur, Elève-Ingénieur de dernière année, réalisa un programme particulier pour générer des échantillons de trafic contenant des difficultés de ce genre - mêmes temps de transit préférentiels - pour un choix d'avions donné, une marge d'indice de coût acceptable et des conditions réalistes d'entrée dans la zone. Ce diagramme est extrait du rapport de stage.*




**Interception en deux temps**
**(b)**




**Interception en un temps**
**(a)**

**Guidage des vols à l'arrivée jusqu'au seuil de piste**
**Séquence des messages de guidage**

**Figure 8**

d'avions pouvait s'avérer très efficace et permettait d'obtenir d'excellents résultats. Le principe est illustré à la figure 7 montrant quatre avions de catégories et conditions initiales telles, qu'ils se trouvent en compétition pour un même créneau préférentiel. La détermination des profils de vitesse les amenant sur la piste dans une séquence optimale résulte rapidement par simple comparaison des situations résultant de glissements des créneaux concernés.

Néanmoins, d'autres éléments peuvent intervenir et pondérer un critère essentiellement économique: c'est le cas de la densité de trafic par exemple et par suite de la charge de travail du contrôleur humain. Ces aspects perçus et quantifiés au cours d'une série de simulations* ont été recensés et font l'objet de recommandations dans un rapport récent portant sur l'évaluation des techniques de contrôle de leur point de vue opérationnel dans un environnement réel actuel, autrement dit, préparatoires à une mise en oeuvre opérationnelle [Réf. 20].

### 2.4 Ordres de guidage et de pilotage

Les interfaces de la chaîne ordinateur/contrôleur/pilote/avion sont discutées de manière suffisamment détaillée au Chapitre 6. Dans ces paragraphes, nous rappelons brièvement les principes qui guidèrent les choix faits au cours de l'évolution du projet et qui prévalent désormais :

- Assurer **la stabilité du système** - à savoir maintenir l'ensemble des temps d'atterrissage dans la séquence des créneaux prévus - malgré les nombreuses sources de perturbations qui tendent à modifier les conditions de vol. A cette fin, un système de contrôle de trajectoire fut développé et testé avec succès dans des scénarios très variés et des conditions atmosphériques difficiles [Réfs. 5, 22].

- Garder la complexité du système à l'intérieur de l'ordinateur [Réf. 23] et **ne présenter au contrôleur que des avis ou directives parfaitement intégrés dans l'étiquette de l'avion** concerné aux moments opportuns [Réfs. 5, 7], sans aucune adjonction d'écran(s) tabulaire(s) complémentaire(s).

- Pour la séquence de directives, **prévoir et annoncer clairement les préavis associés à chaque manoeuvre requise.** La figure 8 suggère la séquence de directives pour deux manoeuvres d'approche distinctes, l'une se faisant en un temps (a), l'autre en deux temps (b). Des exemples du contenu de telles directives figurent dans les rapports de simulation et autres essais en vol déjà mentionnés [Réfs. 5, 7, 20, 22].

---

* *Simulations en temps réel réalisées dans l'environnement du Centre Expérimental avec participation de contrôleurs européens de diverses nationalités (ZOC 1ère génération, 1982), et intégration des techniques de navigation et de contrôle des trajectoires (ZOC 2ème génération, 1988 et 1989).*

- *Simulations en temps réel réalisées dans des environnements groupant le système de contrôle ZOC, les générateurs de trafic et autres fonctions intégrés dans le simulateur autonome STANS et un ou plusieurs simulateurs de vol de compagnies aériennes européennes (Belgian World Airlines, SABENA, Bruxelles; Deutsche LUFTHANSA, Francfort; Nationaal Luchtvaart Maatschappij, NLM-KLM, Amsterdam; BRITISH AIRWAYS, Londres) et du centre de formation AÉROFORMATION, Toulouse.*

- *De plus, le système de contrôle ZOC constitua le système de contrôle fondamental utilisé dans le cadre des développements envisageant l'utilisation des communications numériques automatiques en lieu et place de la radio-téléphonie pour la transmission des messages de guidage et de pilotage entre le centre de contrôle et les avions concernés. Un avion-laboratoire (BAC-111, RAE, Bedford, UK) fut intégré dans un trafic simulé et l'exercice permit de réaliser les premiers essais en vols réels des techniques de guidage 4-D préconisées dans le système de contrôle ZOC [Réf. 21].*

- *Pour poursuivre, une campagne d'essais en vol portant cette fois sur le contrôle d'un bipropulseur, avion relativement lent de la catégorie "Légers" intégré dans le trafic normal est en cours de préparation avancée et devrait débuter au printemps 1994. L'annexe 9A donne un aperçu de l'historique et des objectifs des exercices que couvre cette campagne.*

### 2.5 Etat d'avancement et implantation

Les principes et techniques des concepts visant à la gestion intégrée des phases de croisière et d'approche dans une zone étendue incluant et entourant une grande terminale sont actuellement bien perçus par l'ensemble des autorités concernées. Une revue de telles techniques est présentée au Chapitre 5 et une mise à jour de plusieurs d'entre-elles est accessible dans les comptes rendus du symposium de la Commission Guidage et Pilotage, ***"Machine Intelligence in Air Traffic Management"***, tenue à Berlin en mai 1993 [AGARD CP-538].

De plus, les conclusions du Chapitre 6 montrent clairement la qualité du potentiel actuel, sa compatibilité avec l'avionique couramment disponible à bord de l'avion et son adaptabilité aux technologies futures, communications, gestion de vol et surveillance en particulier.

En résumé, dans la gestion d'une grande terminale, le but fondamental des concepts de la catégorie Zone de Convergence est d'intégrer le contrôle des trajectoires sur une zone étendue évitant ainsi sa découpe à l'échelle des secteurs. Comme nous l'avons dit plus haut, cette phase est bien avancée - en ce qui nous concerne, les développements sont terminés - et, sous des formes plus ou moins développées, plusieurs réalisations sont déjà en exploitation opérationnelle (voir Chapitre 5).

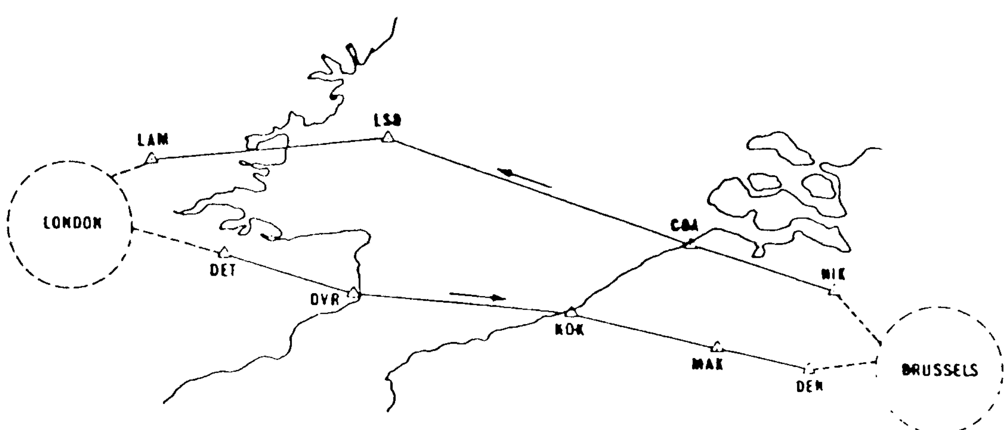
## 3. GESTION POLYTERMINALE *

### 3.1 Gestion d'un vol

Un vol doit être considéré et traité par les autorités de contrôle comme une seule entité. Il ne peut être découpé en une suite de phases qui reflètent la présence de frontières géopolitiques et soumis à une série de procédures de passage d'une phase à la suivante qui traduisent une ignorance non justifiée du mouvement de l'avion.

L'évidente justesse d'une telle approche, les avantages afférents à sa mise en oeuvre, sa parfaite cohérence eu égard à l'évolution du poste de pilotage, poussèrent au développement de méthodes de gestion de trafic, de techniques de guidage des vols et, comme corollaires, de moyens de simulation intégrant l'avion et le pilote dans la boucle de contrôle.

Le suivi d'un vol européen, Bruxelles-Londres par exemple, illustrera plus rapidement qu'un long discours ce souci d'intégration, non seulement à l'échelle de la Communauté Européenne mais aussi aux niveaux nationaux (voir Chapitre 2). Le vol dont la route est schématisée à la figure 9 est successivement pris en charge par cinq unités de contrôle différentes, relevant d'autorités distinctes, abstraction faite de la sectorisation possible dans les divers centres et sans mentionner le contrôle d'aérodrome au départ et à l'arrivée.




**Vol de 45 minutes pris en charge par 5 unités de contrôle distinctes**

**Figure 9**

* *A ce stade, il nous semble utile de reprendre quelques idées fondamentales qui nous sont chères, que nous développons et défendons depuis très longtemps [Réfs. 24, 25]. Cette section est partiellement extraite d'une conférence présentée à l'Académie Nationale de l'Air et de l'Espace, Toulouse, France, dans la série des Colloques Internationaux consacrés à la Sécurité Aérienne et Spatiale [Réfs. 24 et 26 à 29].*

Un vol d'une quarantaine de minutes est ainsi découpé en quatre à six phases entre le lâcher des freins et le toucher des roues. Encore faut-il noter qu'entre les centres concernés par cet exemple, les transferts de contrôle peuvent se faire sans interrompre montées et descentes, ce qui n'est pas toujours le cas. Chaque phase est réalisée de manière quasi indépendante des phases antérieures et ultérieures, et l'avion aboutit de manière presque systématique dans un circuit d'attente, à moins, comme cela se produit de plus en plus couramment, que l'unité de gestion de flux de trafic n'ait assuré un vol direct qu'avec attente au sol préalable, comme suggéré dans la situation illustrée à la figure 1.

Certes dans chaque phase, la sécurité est dûment assurée, mais la structure existante s'oppose à toute notion d'optimisation telle que préconisée par les constructeurs et les acquéreurs de calculateurs de gestion de vol embarqués.

Or, nombreux sont les vols européens dont la durée n'excède pas une heure : de Bruxelles centre exécutif de la Communauté, il suffit de 30 à 60 minutes pour rallier Luxembourg, Amsterdam, Paris, Strasbourg, Londres et Francfort, d'une heure à une heure et demie pour se rendre à Zurich, Milan, Dublin et Vienne (Figure 10).

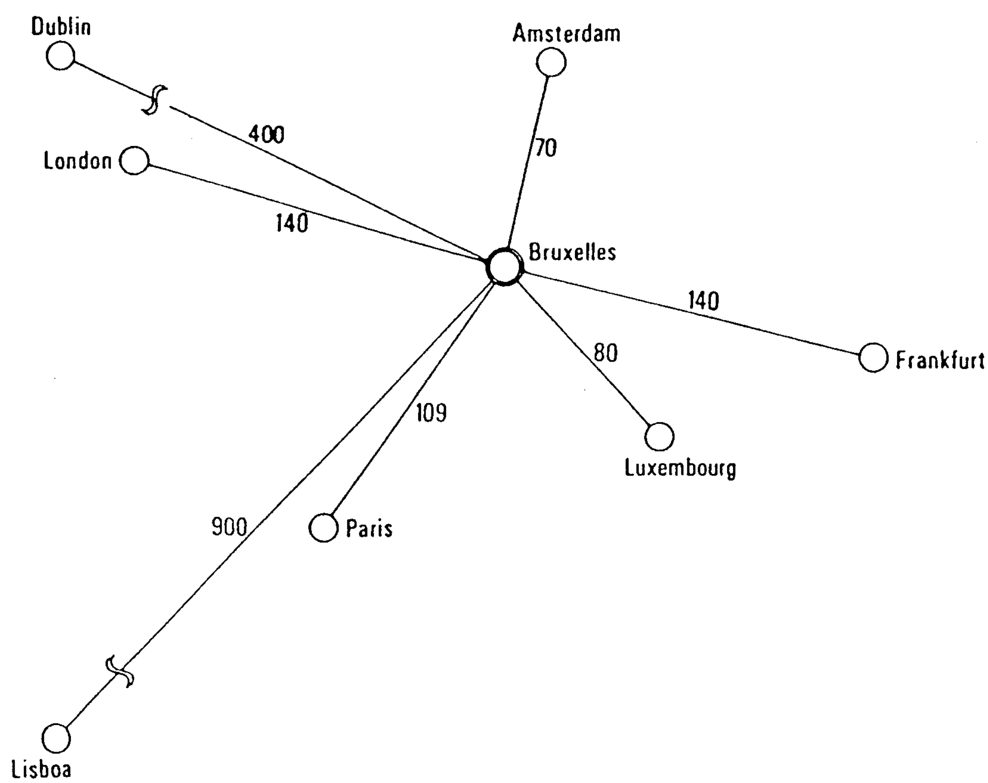
Aussi, tout allongement conduira-t-il nécessairement à une importante augmentation relative du coût, 5 à 10 minutes d'attente cumulée pouvant représenter 10 à 20 pourcent du coût de trajet correspondant.

### 3.2 Intégration du contrôle à l'échelle européenne

L'objectif que nous poursuivons est de proposer pour l'Europe un système de régulation en temps réel de la circulation aérienne dans une région englobant plusieurs grandes terminales, comme celle, par exemple, illustrée et schématisée aux figures 11a et 11b. Dans une telle région, hormis les profils de vitesse, les principales variables de contrôle disponibles pour la gestion en direct comprennent les séquences des instants d'atterrissage pour les vols à l'arrivée ayant leur origine à l'extérieur de la zone et, de plus, pour les vols ayant leur origine à l'intérieur de la zone, les séquences des instants de décollage. Ces deux ensembles de variables sont bien entendu soumis à des contraintes très différentes.

### 3.3 Principe de la gestion en direct

Le système de contrôle en direct intervient dès que l'aéronef pénètre dans cette région étendue. Comme pour la gestion monoterminale, il comporte deux composantes essentielles étroitement couplées, à savoir :




**Jeu de distances (en nautiques) entre terminales européennes**

**Figure 10**

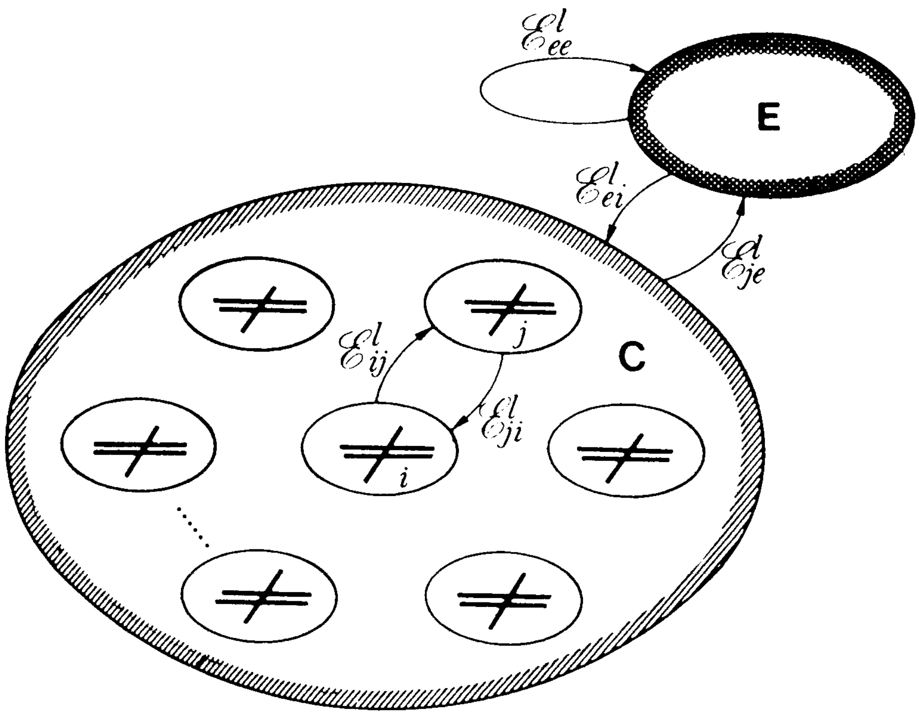
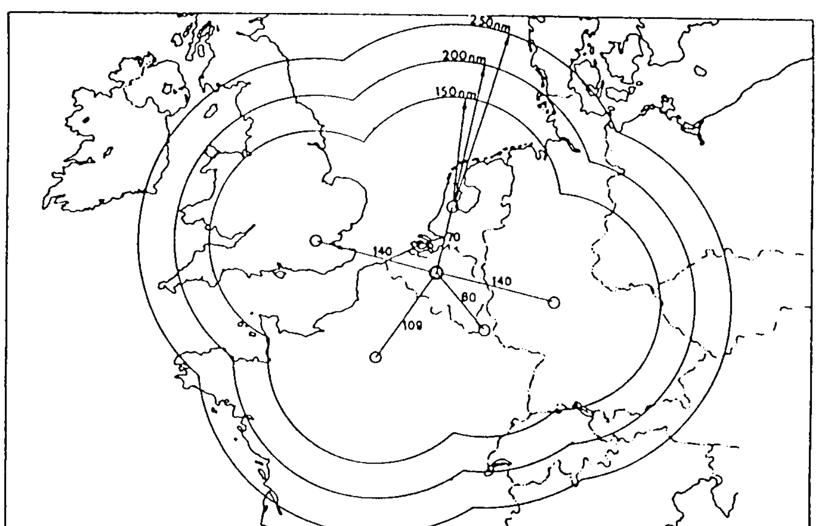



**Schéma de principe d'une intégration étendue**

**(b)**




**Intégration de 5 zones de convergence**

**(a)**

**Exemple d'une zone de gestion et de contrôle étendue**

**Figure 11**

(a) une algorithmique d'ordonnancement reflétant des critères généraux et/ou des priorités momentanées ou locales des communautées concernées (économie, capacité, bruit, etc.) ;

(b) un guidage 4-D asservi à partir du sol, valable pour tous les avions et pour chaque avion/avionique en particulier, capable de fournir des ordres de contrôle cohérents aussi bien pour le contrôleur de la circulation aérienne que pour l'équipage.

Si l'on veut assurer la stabilité de tout système conçu en vue de la régulation efficace d'un courant de trafic aérien et libéré des divers "tampons" que sont, par exemple, l'étagement du trafic ou l'allongement de la trajectoire, tout en permettant à chaque aéronef d'exécuter son vol dans des conditions quasi optimales, il est indispensable de disposer d'un module de prévision fiable, doublé d'un "contrôleur" automatique de trajectoire chargé d'atténuer les effets des perturbations susceptibles d'influer sur la conduite normale du vol, qu'il s'agisse de prévision météorologiques incertaines, de modifications aux plans de vol initiaux, des différentes options d'exploitation des aéronefs, d'incertitudes quant à leurs caractéristiques (y compris la masse et les performances), de l'éventualité d'une erreur humaine (tant du côté de l'équipage que des contrôleurs) ou encore d'autres événements ou incidents particuliers. Dans nos publications antérieures, nous avons présenté plusieurs exemples de tels événements survenus naturellement ou produits intentionnellement au cours de simulations comportant un ou plusieurs simulateurs de vol (vraie grandeur) de compagnies aériennes (voir par exemple [Réfs. 5, 22]).

Comme indiqué dans les paragraphes précédents, une attention toute particulière a été accordée à ces aspects au cours des développements antérieurs (Gestion monoterminale). Désormais, notre sentiment général se résume comme suit :

*La trajectoire d'un aéronef peut être définie et contrôlée avec une précision compatible avec la navigation 4D - à ± 5 à 10 secondes près -, les directives de guidage étant générées par l'ordinateur et intégrées dans l'étiquette radar du contrôleur aérien sans aucune adjonction d'un ou plusieurs écrans tabulaires complémentaires.*

Afin d'exploiter au mieux la capacité disponible, en particulier celle des pistes, il faut que les normes d'espacement soient maintenues au niveau minimum acceptable, voire réduites par une action sur la composante aléatoire des marges de sécurité. Ceci devrait résulter tout naturellement des considérations précédentes, comme l'ont montré plusieurs simulations intégrant des simulateurs de vol vraie grandeur des compagnies aériennes.

### 3.4 Choix de la trajectoire*

Les principes à la base du choix de la trajectoire dépendent de la nature du vol. Pour les vols à l'arrivée - vols venant de l'extérieur -, l'altitude de croisière est en général fixée et le profil de vitesse comprend deux composants, croisière et descente comme cela a été discuté dans le cas d'une zone monoterminale. Pour les vols au départ - destination à l'extérieur -, l'altitude et la vitesse de croisière constituent les variables de contrôle principales, auxquelles il faut néanmoins adjoindre la composante de montée. Pour les vols réalisés entièrement à l'intérieur de la zone, les variables de contrôle comportent la vitesse de montée, la vitesse et l'altitude de croisière ainsi que la vitesse de descente. Notons cependant, que la marge de contrôle disponible à travers le profil de vitesse en montée est relativement réduite.

Ainsi, l'ensemble des choix des trajectoires correspond-il aux enveloppes illustrées à la figure 12, chaque enveloppe étant associée à une altitude de croisière particulière. La figure montre également comment évolue la marge de contrôle avec l'altitude de croisière, reflet de l'enveloppe opérationnelle utile de l'avion.

### 3.5 Principe d'optimisation

L'optimisation de l'ensemble des trajectoires est un problème relativement complexe comme il a été dit dans la préface. Pour l'ensemble des trajectoires concernées, il y a lieu de minimiser la somme des coûts équivalents en choisissant comme point de départ une situation initiale "raisonnable". Suivant la distance à parcourir, il est possible de choisir a priori une loi de montée pratique, figeant ainsi une des variables de contrôle. Il reste alors trois ensembles de variables de contrôle - altitudes, profils de vitesse en croisière, profils de vitesse en descente -, chaque ensemble étant sujet à ses contraintes propres.

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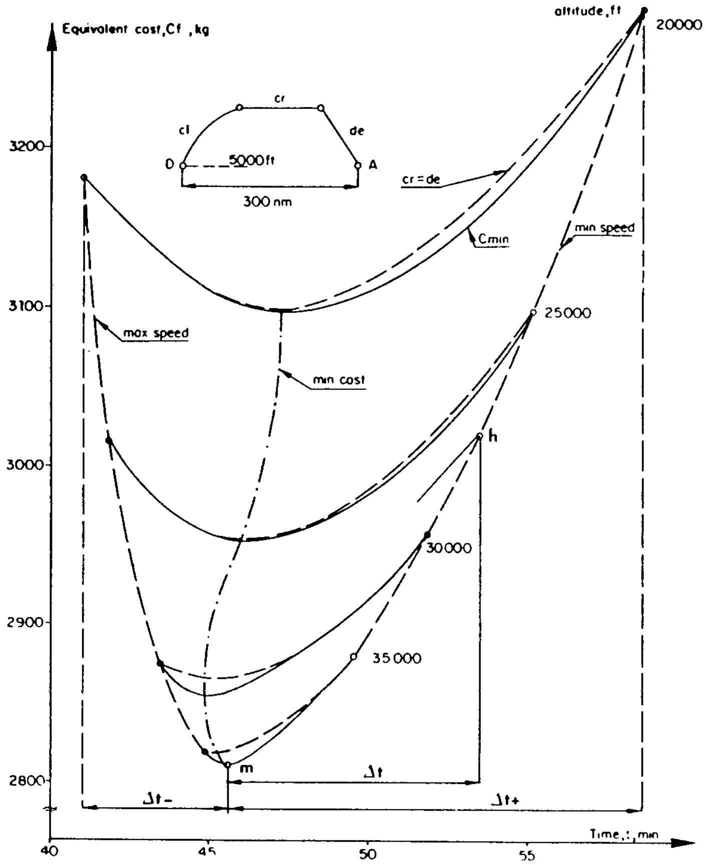
* *La référence [30] contient une liste - non exhaustive - de travaux liés au calcul, à la prévision et au contrôle de la trajectoire publiés et disponibles en 1988.*




**Relation *Coût équivalent - Lois de vitesse - Altitude* pour un vol direct**

**Figure 12**

Au critère d'économie générale, il peut être commode de substituer une stratégie visant à adopter pour chaque trajectoire un temps de transit aussi proche que possible du temps de transit à coût équivalent minimum.

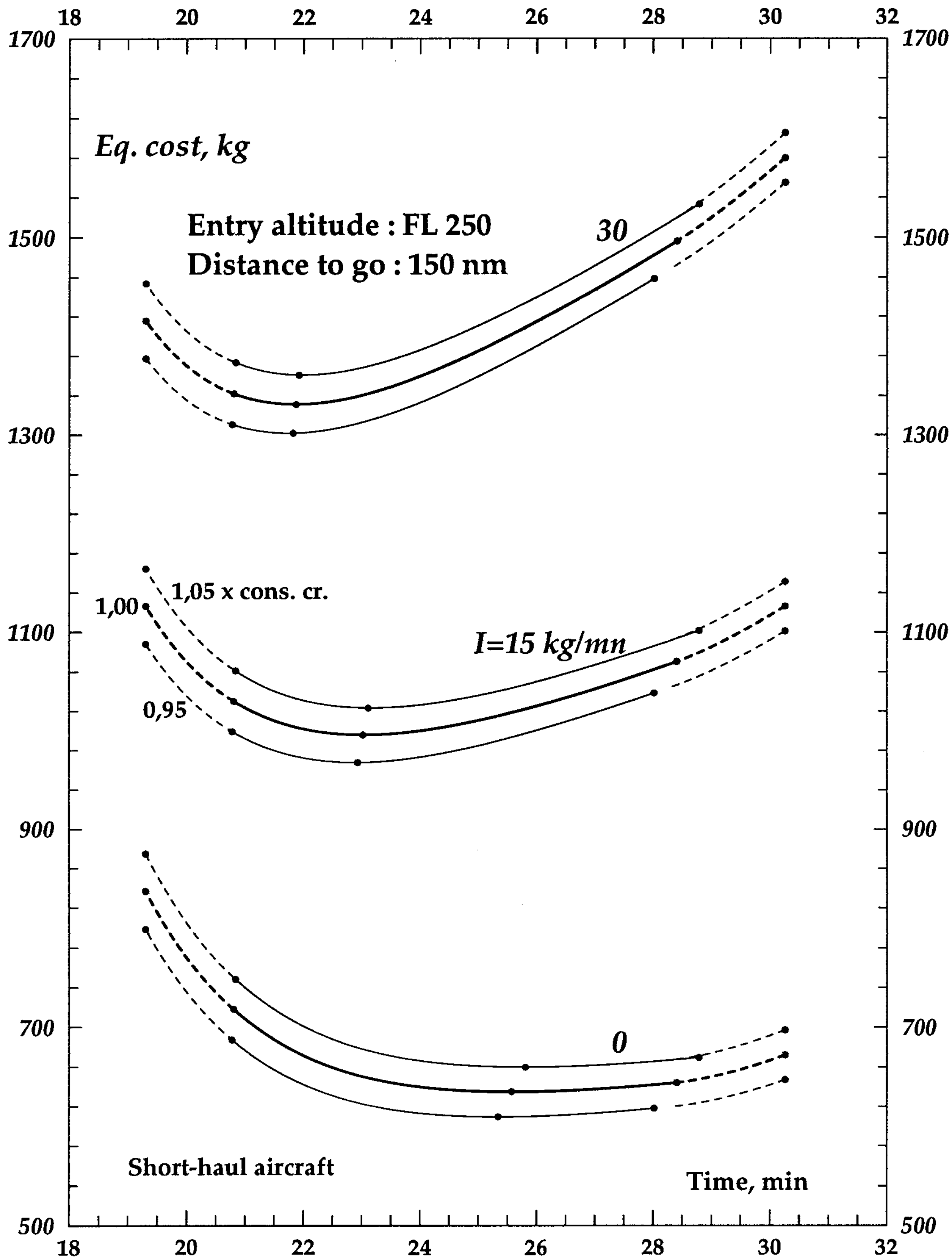
La justification d'une telle stratégie est fondée sur quelques observations d'ordre pratique dont les plus marquantes nous semblent être les suivantes :

- A l'heure actuelle, une compagnie aérienne semble plus encline à fournir un profil de vol préférentiel - voire plusieurs options - sous la forme d'une loi de vitesse qu'une philosophie opérationnelle traduite par des relations de coûts.

- Comme le montrent les diagrammes présentés dans les paragraphes précédents, au voisinage du minimum absolu (pour une altitude et une distance de vol données et un temps de transit libre), l'optimum est relativement peu prononcé.

- Pour tout avion, les consommations spécifiques ne seront connues du système qu'avec une approximation dont la qualité dépendra d'une multitude de facteurs. Ainsi, compte tenu du caractère relativement plat des minima de la fonction ***temps de transit - coût équivalent***, nous pouvons nous attendre à une imprécision relativement importante sur la définition du profil des vitesses qui en résulterait et par suite sur la position du temps de transit optimum. La figure13 tente d'illustrer cette observation pour le cas d'un profil croisière/descente, les erreurs sur la consommation de croisière ayant été choisies égales à + 5 et - 5 pour cent, respectivement. On notera le glissement du temps de transit optimum, alors que l'exemple choisi correspond à une phase de croisière relativement courte et qu'aucune erreur n'entache la consommation en phase de descente.

Cette approche s'est avérée extrêmement efficace dans le cas de la zone monoterminale, mais à ce stade, il est trop tôt pour proposer une technique générale appropriée quel que soit le niveau de saturation de l'espace aérien. Le problème est esquissé d'une manière particulière au Chapitre 8 ; il fera l'objet d'une étude détaillée dans un avenir rapproché.




Influence sur la définition du profil préférentiel
Effet résultant sur le temps de transit optimum

**Imprécision de la consommation spécifique en croisière**
**Figure 13**

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# CHAPTER 7

## A LOOK FURTHER INTO THE FUTURE

# ANNEX

## INTERNATIONAL AIR TRAFFIC HANDLING COOPERATION*

* *This paper was initially prepared for publication in the AGARD HIGHLIGHTS, 93-2, September 1993. It illustrates the intention to cope with both categories of aircraft, those commercial jet aircraft equipped with the most advanced navigation and computerized flight management capabilities and lightweight turbopropulsor aircraft with standard even limited on-board navigation equipment.*

# INTERNATIONAL AIR TRAFFIC HANDLING COOPERATION

André Benoît
Guidance and Control Panel

The aviation world is small. Activities undertaken by apparently disconnected communities may merge, amplifying their own interest and at the same time developing mutual interest.

Under the AGARD support programme for the NATO South Flank Nations, a flight test capability, the CASA 212 Aviocar, was made available to Portugal with the sponsorship of the Flight Mechanics Panel and with the cooperation of the NLR and the Technical University of Braunschweig. This facility is provided and operated by the Portuguese Air Force with tests conducted under the technical direction of the Instituto Superior Tecnico.

In a completely different framework, the European Organisation for the Safety of Air Navigation, EUROCONTROL, has initiated a programme of work aimed at developing techniques for the on-line management of traffic and the guidance and control of related individual flights. The objective is two-fold : minimising the overall flight cost while maximising the use of the available capacity; the system aims to generate, on-line, automated assistance to the human controller at the decision making level.

The Aviocar is now to be used under contract to EUROCONTROL, as part of the programme established for the validation of these Air Traffic Control (ATC) developments.

The Portuguese flight test capability has been described extensively in AGARD documents by Pr Luis Manuel Braga da Costa Campos and his collaborators[1]. In the open literature, Sip Swierstra and other colleagues have presented various facets of this particular ATC work[2]. In this short note, we outline the essential features of the validation exercise untertaken in conjunction with the use of the Portuguese flight test capability.

## 1. ON-LINE TRAFFIC MANAGEMENT AND ACCURATE GUIDANCE OF AIRCRAFT

The Decision Making Aids programme (DMA), a direct extension of the Zone of Convergence project (ZOC), remains as a short term concept, an intermediate step towards the efficient integration of air traffic control over all flight phases for all flights. It is a ground-based approach that is consistent with the effort undertaken by aircraft manufacturers and operators aimed at making efficient use of auto pilots and more specifically airborne flight management control and guidance systems. These will allow aircraft to determine and fly trajectories meeting airline criteria duly adapted to the numerous constraints resulting from the overall air traffic situation.

In the foreseen operational context, both the pilot and the controller remain the key elements of the control system. ***On the ground*** the controller's prime responsibility is to maintain safe separation among the aircraft in his sector. The ground-based DMA system will advise him how to obtain the maximum utilisation of the available capacity considering the flow of traffic through all sectors of a Centre. In the organisation of the traffic flow, specific objectives of the aircraft operators such as minimum cost, fuel or flight duration are considered, leading to a global minimisation of the deviations from the airspace users' preferred flight profiles. ***In the air,*** whenever available, the Flight Management Computer System (FMCS) will assist the pilot in implementing the ATC directives with a very high accuracy, improving the overall control system stability. Future availability of a digital air/ground data link will improve this even further. Given the presence of the human element in the control loop, the initial planning of the traffic flow will have to be based on an average level of human performance and foreseeable constraints. However, in this management and control concept, special attention is given to adapting the control strategy to maximise the system throughput. This is done by automatically taking note of above-average controller/pilot performance and adapting the control accordingly. On the other hand, in the event of any setbacks the system advises the controller how to make the best use of the developing situation.

An update of the state of development was presented to the recent AGARD Conference held in Berlin in May 1993, while the original ZOC concept was presented at the AGARD Conference on "Air Traffic Control in face of Users' Demand and Economy Constraints" organised in Lisbon on 15 October 1982 at the request of the Portuguese authorities.

***In short, the DMA system includes two sets of distinct although highly coupled components, namely decision aids for on-line regulation of traffic and automated assistance for the accurate guidance and control of all individual aircraft concerned.***

## 2. REALISTIC AIRLINE /AIR CREW/AIRCRAFT IN ATC SIMULATIONS

The simulation facilities and scenarios required for the validation should cover, in an accurate and reliable manner, all critical aspects (stochastic, non-linear and discrete) of such a large-scale system, in which the human controller remains sovereign, in particular (a) overall management strategies, (b) ground-based guidance techniques for controlling time-of-arrival constrained trajectories with an accuracy better than 10 seconds - in spite of all the perturbations affecting the conduct of a flight - that is to say, consistent with airborne 4-D navigation, (c) aircraft/avionics/pilot behaviour, response characteristics included.

In addition, the main technological support -surveillance, communications, navigation- should be included, certainly in their present forms but also directly adaptable to foreseeable future advanced technological developments -Mode S and satellite, data link, global navigation.

The two functions, namely the on-line management of traffic, which is re-initiated at least when a new aircraft enters the area concerned, and the guidance of each individual flight, are closely coupled. Nevertheless, their validation and assessment were initially conducted in separate steps: firstly simulation of guidance techniques, with airline crews and air traffic controllers in the loop; secondly, simulation of traffic management strategies, with pilot and controller actions duly represented. Subsequently, we could proceed to full-scale ATC simulations with various levels of sophistication in the representation of the aircraft/avionics/pilot component.

To assess the ***guidance of aircraft*** sub-system, use has been made of full-scale flight simulators - with up to three used simultaneously - operated by airline pilots (Airbus A-310, Aéroformation, Toulouse, France; B-737/200, B-737/300 and DC-10 Belgian World Airlines, SABENA, Brussels, Belgium ; B-737 and B-757, British Airways, London, UK ; City Hopper, Nationaal Luchtvaart Maatschappij, Amsterdam, Netherlands; Deutsche Lufthansa, Frankfurt, Germany; National Aerospace Laboratory, NLR, Amsterdam, Netherlands). In this validation phase, the emphasis has been placed on the human role and consequently on the definition of the related ***interfaces involving either the controller or the pilot or both***. Professional controllers, in particular representatives of the Belgian Régie des Voies Aériennes/Regie der Luchtwegen, Brussels, Belgium, took an active part in the elaboration of the control directives. As a result, it has been possible to refine the guidance advisories to meet both the system objectives and the pilots' and controllers' working requirements. Further, a wide range of perturbations could be covered and the stability of the guidance of the flights sub-system duly assessed.

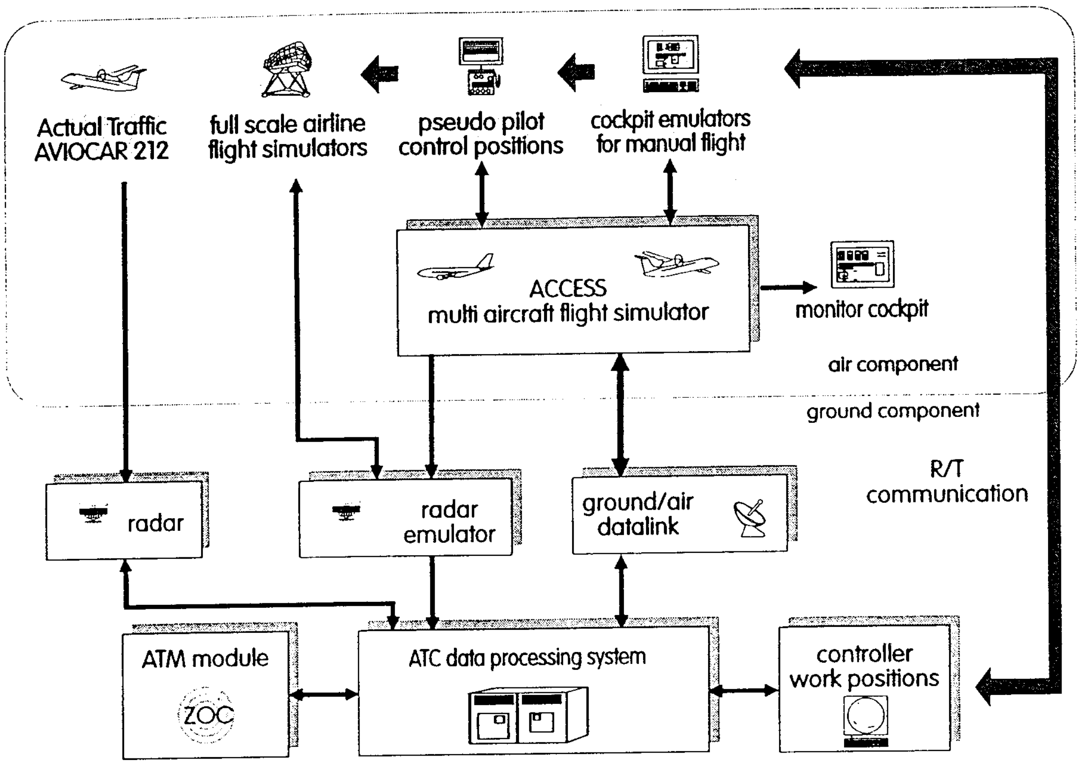
In order to test various ***traffic management strategies*** or to assess the impact of alterations in a basic reference strategy, or to illustrate possible advanced modes of operation in air traffic control, extensive use has been made of a *multi-aircraft flight simulator*, specially designed for such purposes (referred to as ACCESS : Aircraft Control Console for Experiments and Simulation Systems). This approach proved to be extremely advantageous in terms of economy both in equipment and manpower, realism of the air component and ease of operation.

## 3. INTEGRATION OF ACTUAL AIRCRAFT IN ATC SIMULATED SCENARIOS

Accordingly, we have available a low-cost, highly flexible and readily transportable simulation facility, covering possible ATC strategies, present, future and futuristic, for the guidance of aircraft using R/T or D/L communication links, and ready for use in real situations[3]. This Simulation facility for a Total Air Navigation System, STANS, is depicted schematically in Figure 1, where for the sake of this note the actual traffic is represented by an Aviocar.

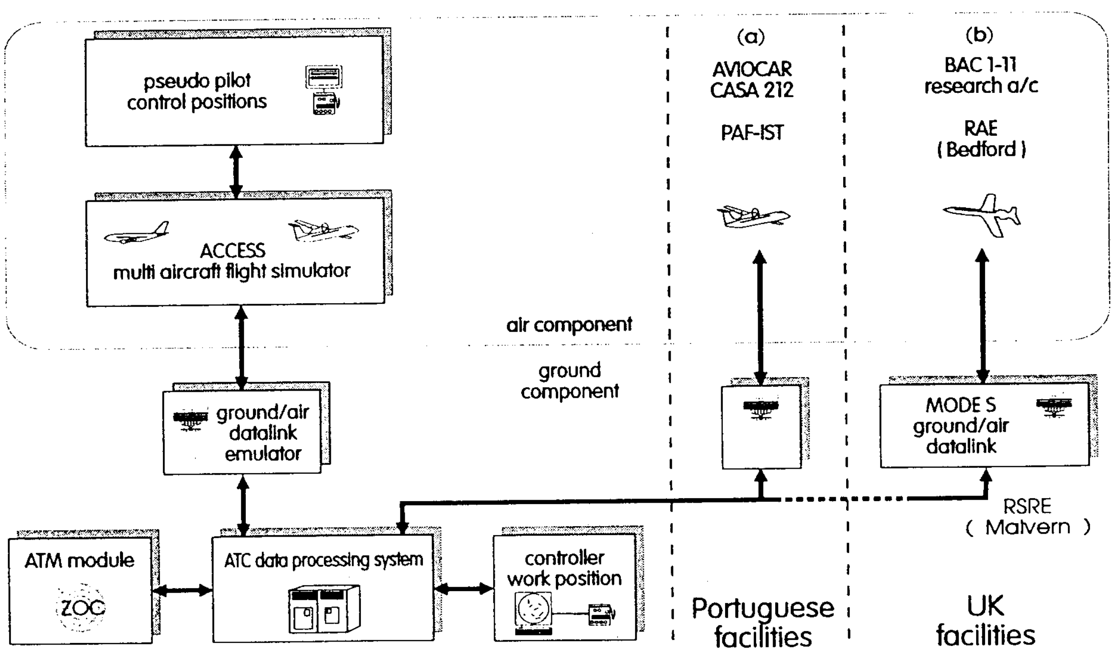
Initially, it was planned to conduct two series of tests, appreciably different in nature, to assess both management of traffic and guidance of flight functions, ***incorporating one real aircraft in the simulation***. The first series would constitute a first, although preliminary, test of the use of the ground/air data link capability -as associated with Mode-S- for ATC purposes, the desired traffic being generated using the ACCESS multi-aircraft flight simulator. The relevant trials were conducted in Bedford, UK., in October 1991[4]. The aircraft used was the laboratory BAC 1-11, fully equipped with Mode S transponder, D/L message display and FMCS configured for 4D-navigation. The second was planned to include a twin-propeller aircraft with standard navigation capability. The experimentation should show the applicability of the 4D-guidance directives to such a category of aircraft. The configuration of the facility for both series is shown in Figure 2.

For the future, the first successful set of trials using the BAC 1-11 shows the compatibility of the proposed development with a possible Mode S, data link environment. Presently, it appears that automatic sequencing of a stream of traffic is in most cases straightforward as long as the range of control of all aircraft in the inbound stream does not differ substantially. This is the case for most civil commercial jetaircraft. However, ***propeller aircraft of the wake vortex category "light" constitute a major difficulty*** in this respect. The operation of these aircraft in terms of procedures and speed range is considerably different from those of jet powered aircraft as are the techniques for the modelling of the aircraft perform-




ASSESSMENT OF GROUND-BASED 4-D GUIDANCE OF FLIGHTS
Illustration of the adaptability of the simulation facility
Single workstation implementation

Figure 1




INTEGRATION OF REAL AIRCRAFT IN R/T AND D/L SIMULATIONS
(a) Twin Turboprop aircraft (b) Research aircraft and Mode S

Figure 2

ance for use in the on-line ATM/ATC systems. As a consequence, streams of traffic which include these types of aircraft are not only complex to process by the automatic ATC algorithms but often cause difficulties in the current "manual" control environment. Accordingly, it was decided to investigate these aspects in a more realistic manner. After having used the Fokker F-27 link trainer in an initial phase, it was decided to include an actual aircraft in ATC simulation exercises. Since then we learned of the existence of the Portuguese flight test capability and the availability of the Casa Aviocar 212 to perform these trials. The programme of work was ready, the preparation of the test campaign is in progress and the first exercise is planned to take place next spring.

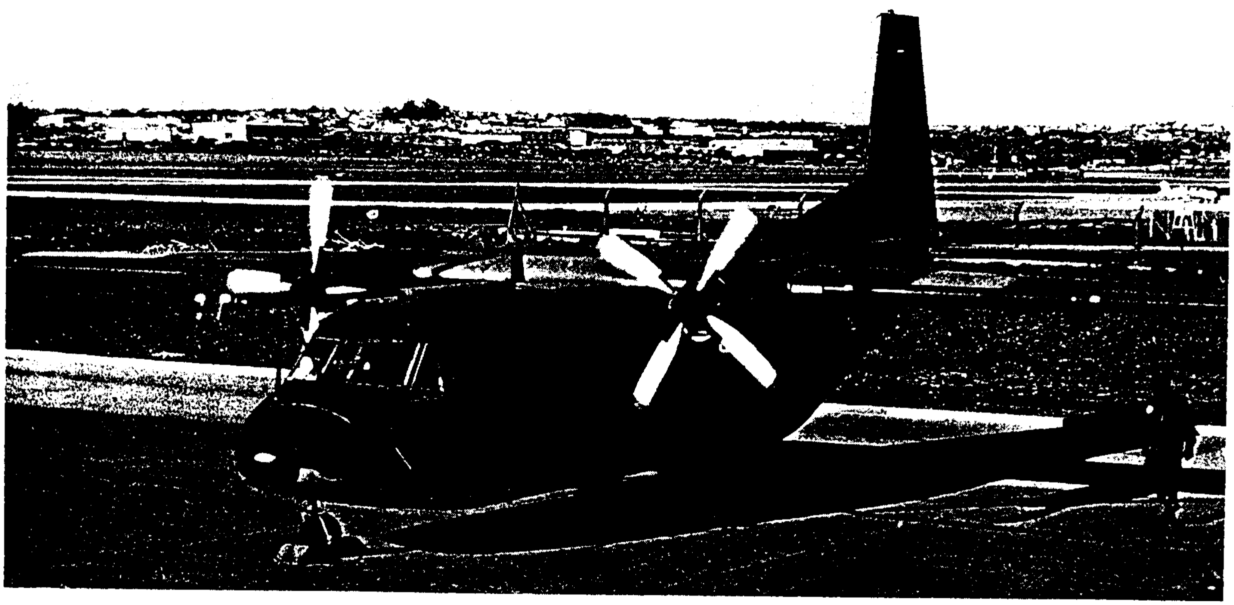
## 4. CONCLUSIONS

*"Improving the co-operation among member nations in aerospace research and development"* is part of the Mission of AGARD. Clearly, the official activities of the Institution, whether Conferences, Lecture Series or others, tend to promote either all or specific recommendations of the Charter. However, informal and/or social events conducted in association with or around a formal activity, a symposium for instance, may have the same, although probably unexpected, effect.

The provision of a flight test capability in Portugal - and its subsequent development - had its origin in a casual conversation between representatives of several European Research Institutions, outside the conference room, at an AGARD-FMP meeting.

In a similar way, at another meeting - the AGARD GCP Symposium held in Lisbon in 1989 - the author became aware of the existence of such a facility... which was precisely what he was looking for.

The next step is outlined in this note. On subsequent activities, a formal report is expected ...



View of the CASA 212 Aviocar

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# CHAPTER 8

## TOWARDS GLOBAL OPTIMIZATION

# TOWARDS GLOBAL OPTIMIZATION FOR AIR TRAFFIC MANAGEMENT

by

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## 1. ASSESSMENT OF THE PRESENT SITUATION

The diversity of regulations due to the souvenir of the sovereignty of the airspace above a country should be abandoned as soon as possible. Let us take an example : a flight between Bruxelles and London. At the (Figure 1) present time is controlled by 5 different centres under various authorithies, without mentioning the sector divisions inside the central zones and the airport control at take off and landing. If the plane is in acent or descent when sector changes, such phases can be interrupted in the vicinity of the boundary (crossing the border in level flight).

In addition, each airline has its own rules which differ even for the same type of aircraft. Controllers try to accommodate with these rules. Pending global optimization, EUROCONTROL is aiming at optimization at least for a large area such as North West Europe. A new division of the airspace (sectors) - as well as a new airspace structure - will certainly achieve a substantial improvement in overall air traffic capacity. Thanks to a study conducted by ICAO, the airspace structure has recently been standardized on a non-national basis which States have been invited to adopt. Some have already done so. France adopted it in April 1992, and the U.K. in May 93 (see Chapter 2, Airspace partition). Other data such as the vertical separation between flights or the FL for the separation of the upper and lower airspaces, should be uniformized on a worldwide basis.

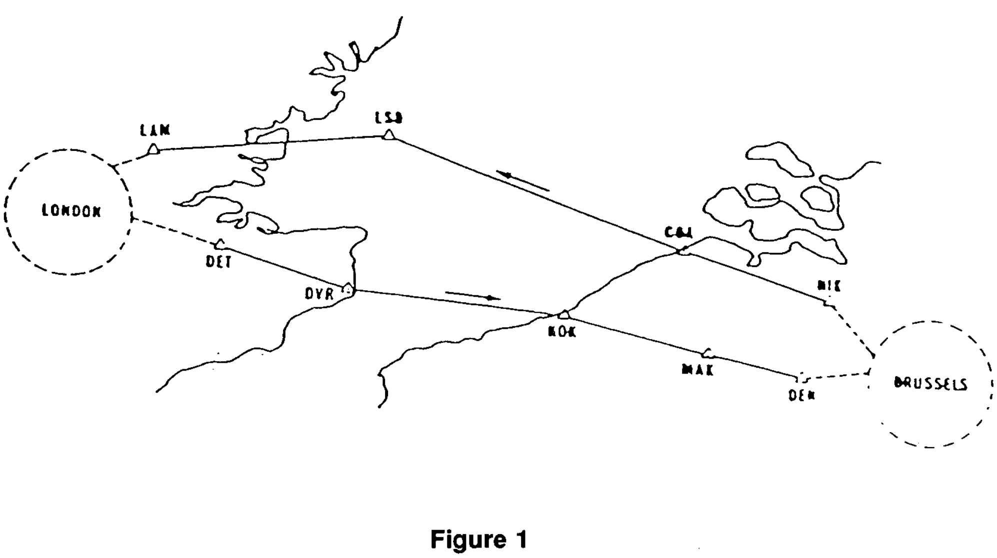



**Figure 1**

**Brussels - London routes**

*Aircraft are highly sophisticated machines.* As mentionned in paragraph 1.1 for modern aircraft a commercial flight can be described as a sequence of automatic phases, engaged manually by the pilot from brake release to landing. In the most advanced aircraft, the flight is under FMS (Flight Management System) control and can be considered as automatic except for acceleration on the runway, "rotation" and the setting of the attitude for the initial climb. However, flights are far from automatic at the present time, because aircraft are not alone in the sky, many interferences with other aircraft occur during the flight and trajectory parameters require to be reconfigured many times, e.g. during climb and descent. Atmospheric phenomenas may impose trajectory modifications. Communications between ground control stations and aircraft are still by voice (VHF or UHF) as they were 40 years ago!

In the near future, man will clearly *still* have ultimate responsibility for decisions although control centres will be increasingly computerized. The minimum level of sophistication to compensate for the precarity of voice transmission is a two-way digital link between control centres and aircraft; messages will be prepared by processors and displayed, and the operator (controller or pilot) will press a button to send the message if he accepts it. He may have to choose one message from a collection presented to him by the processor. In addition, an automatic check is normally introduced by the message read-back. Many accidents are due to misinterpretation of instructions either because of failure to use standard phraseology or because of the poor quality of the voice transmission.

Let us go back to the **FMS** (Flight Management System). Since 1985, most large and medium size planes have been equipped with **FMS**. The computer has, in its memories, a large set of data (airways, airport characteristics and approach procedures, procedures after failures...). Initially it can control directly the "horizontal path" according to the route fed in ; waypoints are automatically detected or estimated thanks to on-board navigation sub-systems links (**INS**, **GPS**, hybrid, will all the ground radio-electric beacons such as **VOR, VOR-DME, OMEGA, ADF ...**). Modern FMS have the ability to control the vertical profile either.

How to use all these facilities, in the best way, to comply with the expected growth of air traffic?

For a long time it has been recognized that a controller is not able to operate on more than 15-18 aircraft in his sector. It has been recognized also that multiplying the number of sectors is not an acceptable solution. A controller optimizes the traffic inside his sectors quite efficiently but he does not take into consideration the incoming traffic from the adjacent sectors. In addition it has been proved that incidents appear more frequently at the borders of sectors than inside a sector.

According to NASA the probability of accidents during a flight (duration 1.6 hours) is mainly concentrated in the descent and approach phases. In Chapter 1, Figure 4 gives the probability of accidents during a flight. Much care should be attached to these phases.

In the final approach, a landing on a 3-degree slope without any flare is acceptable (vertical speed of the order to 3 m/s). Normally there is a flare which reduces the vertical speed at a small fraction of one m/s at the price of a reduction of the available braking distance, sometimes by hundreds of meters and, thence, the safety can also be reduced (for example, in case of brake failure).

Thanks to electronic processed data, the traffic control around an airport (TMA) is well organized and sometimes the approach controller sends messages to the en-route controller in order to delay or accelerate an aircraft before it enters his own area. Here again these messages are only requests, because the approach controller is unaware of all en-route traffic.

It clearly results from these remarks that *only global optimization of traffic from take-off to landing and, possibly from block to block (airport-building gates) should be investigated* in order to cope with the expected growth in the number of aircraft in the next future.

To conclude, it is proved today that Terminal Controllers, aided by electronic systems may feed the "entry point" of the final approach at a rate corresponding to 80 and sometimes 60 seconds separation. It is then clear that either automatic landing with ILS CAT III or manual landings aided by artificial vision (with a high degree of confidence) are mandatory to maintain airport capacity corresponding to good MET conditions when these conditions are poor. In Europe, it can be assumed that, even with poor MET conditions, the separation in time between planes in final approach is rarely below 90 s on average.

## 2. REQUIREMENTS FOR GLOBAL OPTIMIZATION OF AIR TRAFFIC

### 2.1 Optimization process requirements

Before a system is optimized it is necessary to define its *boundary*, the *flows* across it and a *criterion* which is normally a "minimum generalized cost". The behaviour of the system thus determinized by its boundary must be known; the behaviour may be defined on a stochastic basis.

In any public transportation system, *safety must not decrease with the passage of time*; this is a constraint which must be satisfied on a probability basis ; it does not enter into the criterion which corresponds to a "trade-off" between various control parameters in order to reach the minimum of a function (the criterion). This function must concern all the planes present in the airspace considered.

Safety must comply with the following requirements :

a) any instruction given by the controllers should be such that it can be satisfied by flying the aircraft according to the airline's rulebook. In short the representative point in the speed-altitude diagram may be said to stay inside the flight envelope (see Chapter 1, Figure 2). Mathematical models of the aircraft must therefore be stored in the controllers computers. The complexity of the model should be discussed in terms of robustness at least with regard to some parameters such as mass or engine serial if aircraft can be fitted with slightly different engines of a given type.

   In addition, wind gradients in the manoeuvring area should be known or estimated. MET data are not accurate enough for precise 3-D or 4-D navigation. Local wind data can be obtained by interrogating the INS or the FMS, if any. However, no formal procedures between ATC centres and aircraft exist at present - the more's the pity! As we shall see below, that type of data could be available as soon as CNS and ADRS are put into operation.

b) at any time, aircraft should be vertically separated by 1000 ft (and 2000 ft in upper airspace, a distance which will soon be reduced to 1000 ft thanks to the accuracy of altimeters even at very low barometric pressures) and so many nm in horizontal distance according to the type of airspace the aircraft is flying in. To satisfy these conditions a volume of airspace is attached to each aircraft and accompanies it. This is normally a sphere.

In the near future more elaborate airspaces require to be defined, and a "reserved airspace for climb and descent" should be carefully defined in order to allow the maximum number of aircraft in an airspace without adversely affecting the safety requirements.

At a given time, this is an airspace volume surrounding the aircraft and attached to it; it contains all the points that the aircraft could reach within a given time scale (5 or 10 s for example). It can be graduated in "iso-probability of presence" contours.

The volume is provided by synthetic radar plots. It is assumed that the pilot follows the navigation procedures. However, delays and errors due to pilot or automatic pilot should be considered. When a turn is to be made it will be assumed that a delay can be accommodated in the predicted trajectory; only new radar plots may confirm that the turn has been initiated. When the data link is operational (1998) it will be reasonable to assume that the rate of turn of the aircraft (or some data related to it) will be transmitted automatically. In that case the maximum delay will be one ground radar antenna turn, or half a turn if two back-to-back antennas are used. It can be less if digital VHF or Satellite communications are used. The attached reserved airspace would be smaller than the one to be considered at present.

For example, for an aircraft in level flight, the reserved airspaces presence of the aircraft can be shown by its traces on the horizontal plane as indicated on Figure 2a and the vertical plane in Figure 2b.

Normally, these extend in front of the aircraft only. However, investigations on a rear extension corresponding to the wing vortices are recommended in order to protect other aircraft flying in the vicinity, particularly in the landing phase. The safety volume will be used in the optimization process as an "absolute" constraint: the aircraft in question may be at any point in the volume at a given time with an indicated probability. Potential collisions can be deducted from these volumes which change over time.

Note: Today, the "safe domain" protecting an aircraft is much larger than the one defined above owing to the present "separation rules".

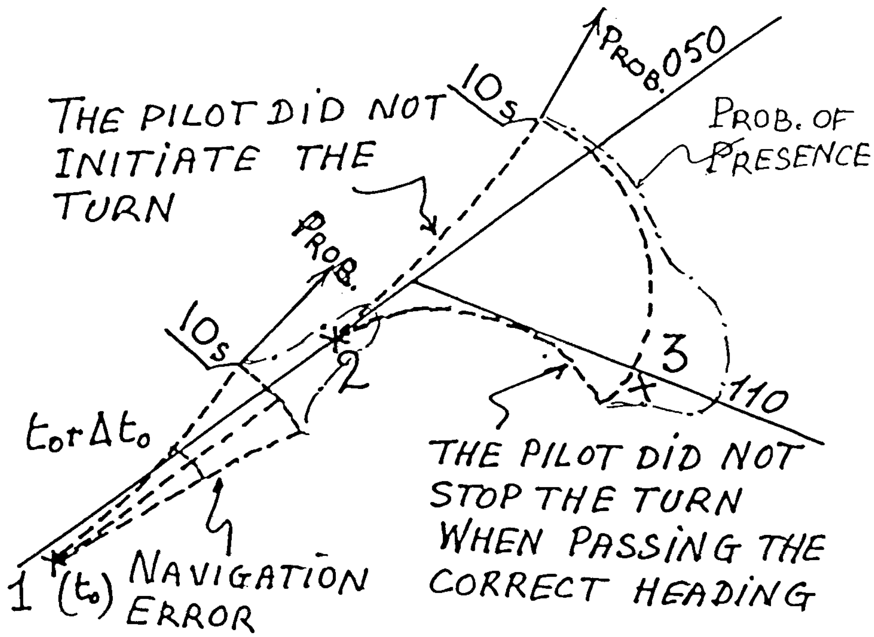
### 2.2 Sub-system considerations

Clearly "Air Traffic" includes aircraft movements at airports because ground movements may interfere with the rate of take-offs and landings at an airport. We think that ground movements should be automated by means of automatic tractors or, at least, should be controlled through a centralized management system, like trains are in a large station (see chapter 10). We propose that flights be considered from "*block to block*".

To be effective, global optimization should be world wide... However, real optimization should be consistent with :

a) the power of optimization theories and their correlative algorithms;

b) the power of computers which can be used at the time the optimization is performed;




**1, 2, 2 Radar plots : the "Probability of Presence curve" is recomputed after each radar plot ; it takes into account the 2 or 3 previous radar plots.**

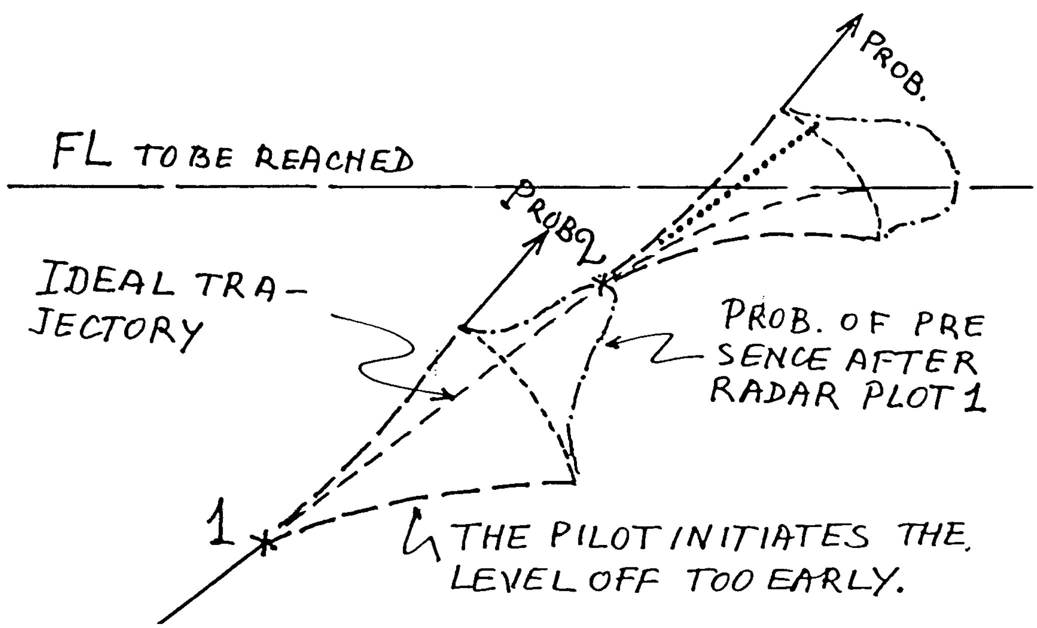



**Figure 2a and Figure 2b**

**Probability of Presence of the aircraft, level flight (above) vertical plane (below)**

c) the availability of coherent data to feed into the system (time-position, flight plans (PLN) and MET data).

Fortunately, the whole world can be partitioned into sub-systems which appear as fully or, at least, fairly decoupled. So, the North West Europe area can be considered as a sub-system fairly independent of other high-density areas such as the East and West sides of the USA or Indonesia. This does not mean that traffic going to or coming from these or any other areas should be ignored. We said that the definition of a system implies knowledge of the flow across the boundary. Outgoing and incoming traffic should be identified in the future by their densities at entry or exit points on the boundary. The accuracy of the time description of these densities will be discussed later on. For example, we think that an area including the airports of the following five cities and an area extending 200 miles from them, could be considered as a self-contained area and optimized: London, Brussels, Amsterdam, Frankfurt and Paris.

Global optimization implies abandonment of the sector concept as it stands today.

The abandonment of sectors does not mean that traffic will cease to be controlled by different centres operating in different geographical areas. But these areas should ignore political divisions; they will be related to traffic densities rather than to sovereignty. Abandonment of the sector concept, as it currently stands, does not mean that sub-optimisation is not sought for instance in an area which is considered as non interfering with its exterior. But such areas, within which local optimization is performed are not defined once and for all ; their sizes are determined from time to time according to current traffic density - let us take an example.

Incoming and outgoing traffic passes over 4 to 8 entry/exit points. Routes converge at the entry point and diverge from an exit point. The area A inside these points, which contains the airport, is fixed once and for all; the optimization criterion inside this area could be "feed the entry points in such a way that maximum landing rate is achieved without penalizing the take-off rate as estimated by the CFMU and in agreement with prevailing MET conditions". The distribution of the rates among individual entry/exit points is part of the optimization criterion. In fact, the controllers aided by the optimization computers have very few options, and the control parameters are also limited : angle of interception of the ILS axis, small changes in velocities, exceptionally a holding pattern. Later on, we shall attach penalization coefficients when an aircraft is required to make changes with regard to the "declared optimum trajectory", in any way it does not seem advisable to attach any penalization for trajectory alterations inside area A, which corresponds to the TMA.

Adjacent to area A, areas $Z_1$ , $Z_2$... could be defined ; their connections with area A are at the entry/exit points (see Figure 4 of paragraph 4.1; A in the TMA, $Z_1$ is area II...). It will be suggested that areas $Z_1$, $Z_2$... are not defined in size once and for all; they could be defi-ned according to the traffic densities in such a way that traffics in each area be as much as possible decoupled from the adjacent area. In each area conflicts must be detected and solved. Optimization is performed in each area and in adjacent areas : the criterion used is "minimum penalization over as large an area as possible".

Another question should be discussed: this is the way in which penalization coefficients already obtained for traffic coming from outside the "Area considered for global optimization" i.e. North West Europe (NWE) can be taken into account. For example: an aircraft coming from New York has accumulated some penalization due to delays by Atlantic Control. If it is supposed to land at Brussels, will it get some kind of priority when entering the NWE area ? Could that be acceptable or should we ignore the penalization already accumulated, or should this be unfair and should we imagine some kind of reciprocity ? A compromise may be sought, e.g. some kind of relative value with regard to the duration of the flight from take-off to the time of entry into the NWE area.

A central computer or supervisor would control a wide area, for example, the NWE region. It would be connected to secondary or slave computers, distributed among areas mentioned above. Optimization may be conducted on central or secondary computers according to the type of event (see paragraph 2.4) which called for a new optimization.

Local Processors operate on areas I, II and III (Figure 4) mainly to solve conflicts ; global optimization is performed by a "Global Optimization Processor".

It should be noted that the division given in the figure corresponds to a main trunk A to B. Unit I may control other routes, either from A or from other airports such as C and D.

A sub-area acquires radar data and report data from crews when passing over beacons on way points or when changing FL. These data are transmitted to the central computer as well as all other data which should be considered in the optimizing process. However, local conflicts may be processed at the slave computer level if it is proved that the conflict has no interference outside the sub-area.

### 2.3 Criterion for optimization; present situation

The flight profiles of all aircraft present in the area to be optimized are determined by the criterion. The traffic varies daily, weekly and seasonally: the criterion may take into account these variations, but it seems simpler to use a collection of criteria according to the situation.

On the basis of past experience, flights are pre-scheduled every day 12 to 24 hours in advance, in order to smooth the peak hours. No optimization process is used for such pre-scheduling.

Before departure a "Flight Plan" (PLN) is filed and transmitted to the central centre. The PLN mentions the identity and requirements of the aircraft, the preferred route, the preferred cruise altitude, a time slot for the departure time and some other data concerning the aircraft equipments.

Such a PLN ignores any other traffic and, if the plane were alone in the sky, would approximate to the "optimum" flight. However, an airline may decide to use a longer route than the shortest one if it knows that the probability of congestion on the shortest route is high. This is a guess, not the result of a quasi real-time optimization. After studies, the PLNs in the future may possibly not mention any route but just the departure and arrival airports, the route being determined by the central computer.

Even if an aircraft is alone on its route there is no single criterion for the optimizing process. Constraints exist. The optimum profile for an aircraft in the cruise phase would be a continuous increase in altitude in order to fly at constant CL/CD for an optimum thrust setting. That is difficult to accept in the management of the entire traffic and there is little likelihood that a vertical profile of that type could be taken into consideration in the management algorithms before year 2010 or 2015. The 2000-ft separation - soon to be reduced to 1000-ft - and the use of constant Flight Levels are the only possibility for a long while yet.

If the aircraft is no longer alone in the sky and none of the other flights interfere with each other then the airline profile can still be used and all flights are considered as optimum ones. As soon as one flight interferes with another, or others, compromises must be sought.

Actually, in many cases small alterations of the predetermined profiles will solve the problem. This applies to crossing traffic. Alteration may consist in :

a) minor temporary deviations from the 2-D route along a leg (dog legs);

b) change in the FL for one aircraft;

Note : For many reasons a temporary change of altitude, say climb 2000 ft, level off for a few minutes and descend to the initial altitude, is not at all advisable. FL changes should be kept uniform as long as possible (altitude increases or altitude decreases by steps).

c) a major temporary deviation from the 2-D route such as a 360 degree turn in order to hold the aircraft;

d) a new 2-D or 3-D route.

The penalization due to these alterations may be computed according to a criterion; normally the criterion used is the sum of two or more terms:

- the increased fuel consumption due to the manoeuvre;
- the additional flight time;

these terms, weighted by coefficients, are those normally considered at the present time by all airlines.

Note : A threshold should be specified for penalization; for example an alteration of types a) or b) would probably produce a negligible penalization, while alterations of type c) or d) are definitely penalizing.

Another type of interference comes up from MET prediction and, mainly, wrong wind prediction. Winds vary in space and time. Prediction of interferences should therefore, be revised periodically. But no penalization due to wind can be claimed by the airline. Only the way to solve a conflict (an interference) should be entered into the optimization algorithms in order to minimize the global penalisation.

Note : For constant IAS evolution, 2-D trajectories may be altered if the pilot does not compensate for wind. This should be kept in mind, namely for "vectoring control" (the controller sends headings to the aircraft).

Another type of interference (and the most frequent one) is encountered at the terminal because of the limited capacity of airport runways. It will be assumed that during a period of between 1 and 3 hours the number of landings per runway is a given parameter (60 to 20 landings per hour, depending on MET conditions).

The aim of the optimizing algorithm is to feed the "entry gate" prior to final approach at the maximum rate once saturation is reached. As previously stated, this feed rate is considered as the main goal for

optimization algorithms, minimization of the global penalization to achieve it being the second goal (objective) of optimization algorithms.

In some cases the optimum profile set by the airline may differ from the standard one, for example, when an airline wants to go faster in order to compensate for a delay experienced prior to take-off. At the present time there are no rules to accommodate such requests except by a dialogue between the crew and the control centres. Landing at a specified time is clearly a very important goal for airline operators. This is why each cause of delay in the scheduled landing time must be carefully analyzed and processed in the optimizing criteria for the benefit of all.

Some data concerning the airline profiles are mentioned in the flight plan and the ATC units try to accommodate them. No global optimization is automatically achieved by ATC computers and no global solutions are presented to the controller ; temporary changes (for a given flight) of such profiles are handled by dialogue between crew and ATC.

Airlines use basic "cost indices" and invite their pilots to minimize flight cost whenever possible. A typical cost index is :

$$C = a\,\Sigma\,(\text{Fuel}) + b\,\Sigma\,(\text{time of flight}) + c\,\Sigma\,(\text{delays})^2 + d\,\Sigma\,\Delta\,(\text{OETA})\ ;$$

OETA = Original Estimated Time of Arrival ;
a, b, c, d coefficients to be adjusted;
$\Delta$ means the deviation with regard to the OETA.

In the case of the last term, which seems to duplicate the 2nd and 3rd terms, it is noteworthy that take-off delays and additional en-route delays do not have the same impact. OETA delays produce over-penalization in terms of take-off delays, because this compromises the re-scheduling the airline might prepare at the landing site for transfer flights. Sometimes a term corresponding to the square of the delays is added.

Such "cost indices" are thought not to allow global optimization because (a) they are not homogeneous (they combine time and fuel consumption) and (b) no global consensus exists between the users. Consequently, the resulting flight profiles will depend on the diversity of cost indices and will thus not be "neutral" as far as the airlines are concerned.

## 2.4 Some definitions

**Event** (definitions) :

a) the initiation of a flight (take-off or passing the exit way-point of the airport area);

b) the termination of a flight;

c) the entry or the exit of a transit flight into the zone to be optimized;

d) the entry or the exit of a flight departing from, or arriving at, an airport in the area considered;

e) an identified incident on an aircraft (engine failure for example).

Any event leads to a re-optimization of the global traffic unless it can be proved that the event causes a local disturbance which does not interfere with other traffic.

**Singularity :**

It is suggested that a point (3D) on a route having at least one of the following characteristics should be called "*singularity*" :

- a 2D route passing over a "beacon" such as : VOR or VOR-DME, ADF ;

- designated point called "way-point". The 2-D coordinates of the point may be data from 2 VOR, data from 2 DME or a combination of these, Lat/Long data ;

- designated point called "*Airport entry*" and "*Airport exit*" ;

Note : splitting or fusion of routes are normally performed over such "singularities".

- TOD (Top of descent) is the point at which the pilot initiates the descent : *it is not a fixed point on a route*; however it is a point normally defined and decided some minutes before it is reached either by the crew, or by ground control ;

- change of FL is also a singularity because it implies coordination with other traffic; such points are not fixed on a route.

**Other definitions :**

**Atmospheric Disturbances :**

Active storms : are normally localized by MET and Air Traffic Control centres are informed. They could be detected by on-board radar when installed. Aircraft should avoid them, but they should get a clearance from ATC for any de-routing.

Icing clouds : are more difficult to detect by on-board radar. ATC is supposed to know their position and activity and give advice to air crew.

Winds : These are the main cause of atmospheric disturbance. The location of high and low pressure

areas is quite good, as well as the iso-pressure contours. The winds turn around these areas in opposite directions (the low pressure is to the left of the wind); in between two high pressure areas, or low- pressure areas, winds will change in direction roughly by 180 degrees. It is difficult to determine with any accuracy where the change in direction occurs and such an uncertainty in this vicinity makes forecast quite hazardous.

This is why criteria should be robust with regard to estimated winds. Winds are normally re-estimated every 4 or 6 hours; even just after a re-estimation large errors may be present (30-degree deviation and/or 20-40 kts error are common in some areas). The aircraft should compensate for these errors in order to maintain a 4-D trajectory as predicted. Note that, locally, these errors act upon all aircraft in the same way, and within a given space safety may not be affected. However, it must be remembered that these errors are not constant over a large area : crossing traffic will be affected differently.

It is also important to note that in the vicinity of the airport, 2-D routes are composed of small legs and sometimes wide turns; winds and wind errors should be considered in order to maintain both the requested separation between aircraft and the estimated time of arrival (ETA) over the final beacon.

**Airports disturbance :**

- Aircraft ground movements, occupancy of gate for a longer time and ATC requirements may cause delays at take-off with regard to the scheduled time.

**Constraints** : these are standards which should never be infringed: the separation distance between aircraft or between aircraft and fixed obstacles (ground profile, antennas, pipes...) or, which should be satisfied "at best" such as noise reduction.

- **Restricted/prohibited** areas : in the case of "vectoring" or "free routing" (see below) aircraft must never be guided to fly over these;

- **Take-off and noise reduction** : full power must be reduced as soon as a "safe height" is reached;

- **Airport curfew** - at some airports landings (and take-offs) are prohibited after a given time (normally 23:00 hr). Aircraft must be re-routed forward to another airport if the landing time at the destination airport fails to comply with the curfew. When such an event occurs, the penalty for the airline operator is very heavy.

- **Vectoring - Free routing** - It is possible to instruct an aircraft not to stick to the route network. A clearance is given by the ATC to use a direct trajectory from point A (it could be the present position of the aircraft when the clearance is issued) to point B (normally a beacon or way point). "Direct route" may have different meanings. In the case of a long distance it means a loxodromic or orthodromic route; in the case of a short leg, in a congested area, it is normally a "radial" from beacon B. Free Routing or vectoring is always subject to ground control and must not interfere with any other traffic. It is a succession of short legs or turns. Vectoring is very often used when traffic density is low, or in the terminal area around an airport.

  Free routing is used over low-density regions for long-haul flights. Note that the North Atlantic Ocean is not a low-density region.

**Saturation effect**

It has been proved that in any problem where saturation may occur, the flows just before saturation are higher than the flows once saturation is just established. Consequently, it is important to study the performance of the optimization algorithm with regard to saturation time occurrence, in gradually increasing traffic density.

**4-D trajectories**

Predicted trajectories are rather like "tubes" with "possible dates" than traditional 4-D trajectories. The predicted scale of presence of an aircraft vary according to the time-horizon of the prediction. Estimated wind profiles (more precisely the gradient of wind profiles) should be considered as parameters, and the robustness of the algorithms with regard to wind uncertainties should be estimated.

**"Event" occurrence**

The events described in paragraph 8.2.4 can be called "positive events". To them we propose the addition of "fuzzy events" such as minor deviation from the nominal assigned trajectory (X, Y : ground sequence; Z : barometric reference or ground reference of on ILS).

Here again it seems worthwhile distinguishing the En-Route and Terminal cases for detailed study purposes.

We again assume that we start from a smooth optimized situation and that an event occurs.

How should a new optimization process be initiated ?

Suggestions :

α) Estimate the disturbed airspace so as not to send new instructions to too many aircraft (see paragraph 3.5). This is an iterative process to be consistent with the global optimization concept; it may be advisable to impose a penalty if *too many changes occur in a given interval of time*; for example: if there was no flight profile modification during the last XX minutes then a modification will be penalized ΔP depending on the type of modification. If there was a flight profile modification within the last XX minutes, then ΔP is much greater.

β) Find the minimum penalty for all the aircraft inside the disturbed airspace. To solve the conflict(s) use the rules with the corresponding penalization ; these penalties depend upon where they occur (En-Route or TMA).

γ) After traffic is rescheduled in the area, global rescheduling can be considered if improvements resulting from minor correction can be combined and implemented.

**Anticollision Systems**

T-CAS II is or will be soon mandatory in most major terminal areas. There is no communication with ATC, the manoeuvre must be accepted by the ATC and ignored for the penalization budget. It will be the same for T-CAS IV (T-CAS III is abandone)d. However, new systems are under consideration at the present time. Some of them are based upon "*repulsive potentials*". They only need correct detection of the aircraft by each other. The evasive action is derived from the potential resulting from the combination of all the potentials attached to each aircraft pair : therefore the ATC, which has good knowledge of the position and speed of all aircraft may use the same concept, and compatibility between the evasive action computed on board and the one computed at the ATC level is insured : safety will gain [Ref. 1].

## 3. SUGGESTED CRITERIA FOR GLOBAL OPTIMIZATION

### 3.1 Flight envelope

In this chapter we just stated the problem of global optimization as we see it. It is quite evident that, if traffic increases as it is expected the present Air Traffic Management concept will become obsolete soon. A new approach should be looked for; a suggestion has been given here, but other approaches are probably as good at this one. The success of the proposed approach needs a "global" consensus of Airlines Operators as to the penalisation attached to any modification to the optimum flight profile for a plane, at a given T.O. mass, for a given range. Then a neutral optimization performed by a computer may impartially lead to a global minimum penalization in real time of all the planes concerned in the zone; the larger the zone, the better the optimization: it is thought that the North West part of Europe with 6 major airports could be considered for a feasibility study.

We propose to start from the aircraft's "*flight envelope*" (see Chapter 1 Figure 2). For a given mass, balance and load factor the manufacturer establishes a flight envelope. (true air speed in abscissa ; altitude -at referen.e 1013.25 hPa - in ordinate). Certification authorities approve this diagram which is composed of several domains :

a) the "never exceed" domain, which corresponds to the maximum velocities that the aircraft can experience in flight; they are proved by flight tests, but they are not acceptable in normal operational conditions;

b) the "max operational" domain, which is inside the previous one, is the whole acceptable domain;

### 3.2 Cruise phase

Let us consider, first, the cruise phase. For a given range, the airline sets the optimum point, for example $M_1 = 0.78$ at $Z_1$= FL 330 (Figure 3a). We give a weighing coefficient, that can be called *penalization coefficient*, of 1, to that point. If for control purposes the plane is invited to fly with different parameters, for example M=0.80 FL 350, the company may claim for a penalization of say 20% which corresponds to a *penalization coefficient* of 1.2. Thus, we can draw iso-penalization contours around the point ($M_1$ $Z_1$), and quote them as indicated in Figure 3b.

As said previously, slight alteration of these contour lines, as well as the centre point quoted 1, may occur when mass (or balance) varies. The sensitivity to mass is well known and we assume that a reference diagram, with the correcting rules to cover the whole range of mass and balance which the aircraft can fly, could be provided to the Air Traffic Management staff *once and for all*, for each type of aircraft.

However, as we have already seen, an airline operator may want to modify the optimum point for justified reasons, for example, in order to compensate for a late departure and try to arrive on time (heavy aircraft proceeding to a "Hub" or aircraft experiencing a strong tail wind, where speed is reduced in order to arrive on time and save fuel). In that case, the airline may send a message to the ATC centre saying "the optimum

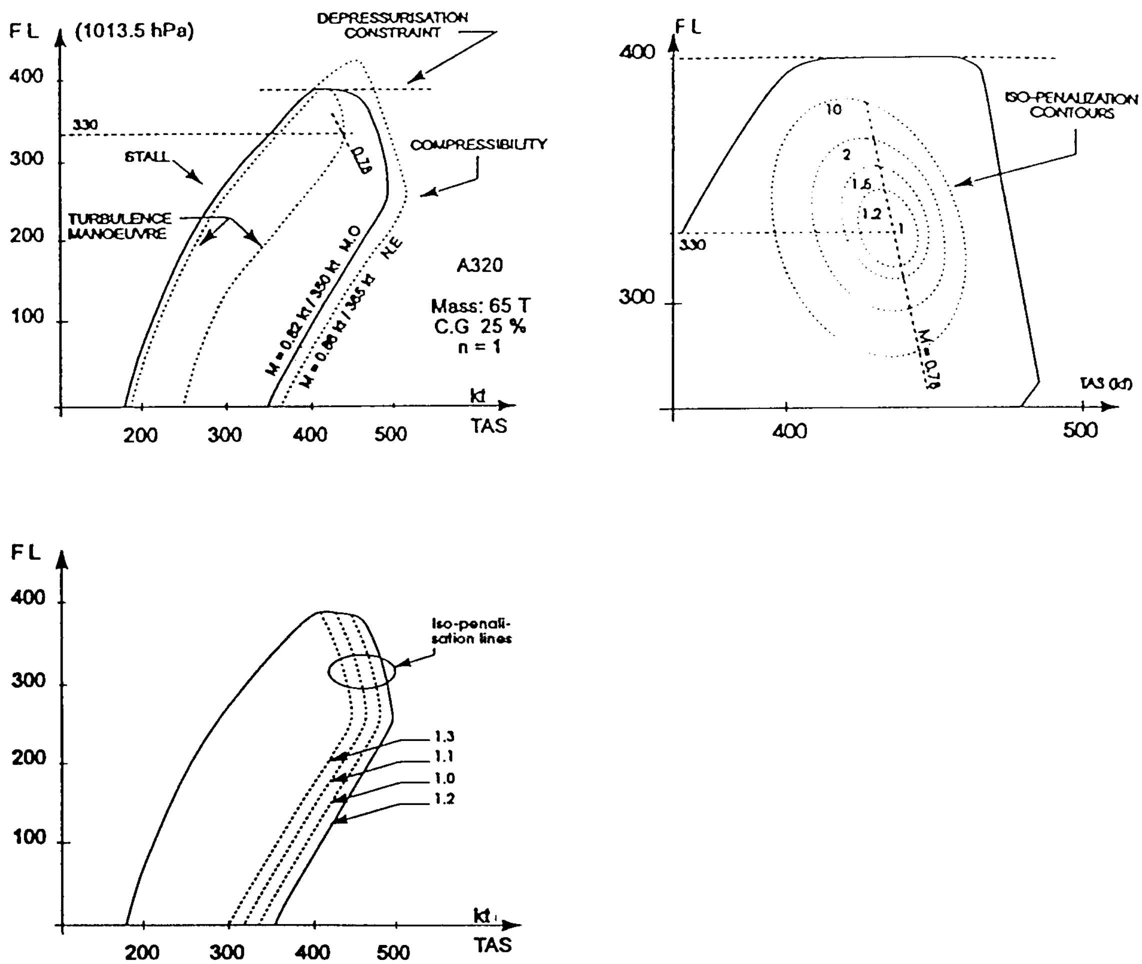



**Figure 3a, 3b and 3c**

**iso-penalization lines**

setting for **that** particular flight is ($M_2$ $Z_2$) instead of the "usual one" ($M_1$ $Z_1$). Like in the preceding case (sensibility to mass) we can assume that a *unique algorithm* stored in the computer will re-quote the iso-penalization contours around the new and temporary optimum point ($M_2$ $Z_2$).

### 3.3 Climb phase

Let us now consider the climb phase: for the long range flight, any penalization encountered during the ascent will have small effect on the whole penalization over the flight. The global optimization being made on a limited time horizon, the risk of penalizing the long range flight during the climb disappears.

Normally ascent is performed at constant indicated airspeed. "Constant indicated airspeed" happens to be not far from the optimal ascent for an aircraft. Iso-penalization contours are the constant indicated airspeed lines, easy to graduate (Figure 3c).

More difficult is the penalization value to be attached to a level-off during climb (for traffic requirements or when passing from a sector to an adjacent sector) or to a combination of speed and rate of climb modifications. Penalization should be completely *non-*

*dimensioned* as it is in the cruise phase. It should benoted that such events (level-off - take $V_1$ instead of $V_2$) have normally a minor impact on the penalization cost in the case of a long flight, but on short flights they can be penalizing and a penalizing coefficient covering the climb phase should be defined. We call these penalizations "discrete penalization" (see paragraph 3.7).

### 3.4 Descent phase

Let us now consider the descent : in calm air, the optimal descent is to use idle power and arrive at the prescribed FL (or altitude) right on the beacon or way point. A descent cost index is easy to derive from the above "optimal descent". For example, if descent is requested before the optimal "Top of Descent", the airline may estimate the additional cost (fuel + flying delay), and arrive at a non dimensioned coefficient as indicated in Table 1 This is a "discrete penalization".

Holding: If holding is necessary, a table similar to Table 1 can be derived (figures are not the same because aircraft are put into an "economic state" : reduced power and flaps). Here again, fuel is proportional to the time in holding but penalization for additional flying time increases more rapidly with regard to time.

### 3.5 Optimization process

Let us now assume that the penalization contours, the associated algorithms to take into account actual mass and balance and the algorithm to re-quote the iso-penalization contours when the optimum point is exceptionally moved, are **accepted by all users of a type of aircraft**[1]. Then a real global optimization can be engaged. It can be stated like this : at a given time, find the optimum set of parameters (M, Z) for each aircraft, which produce the *minimum global penalization* over the next 30 mn (a figure open to discussion), given constraints such as:

| Anticipation | Penalization Coeff. | Note |
|---|---|---|
| 30"<br>1'<br>1'30"<br>2'<br>3'<br>4'<br>5' | 1.1<br>1.2<br>1.3<br>1.5<br>1.7<br>2.0<br>3.0 | It seems that the additional fuel is proportional to the delay; the penalization due to the increase in flying time is not. |

**Table 1**

- separation between aircraft, which must always be maintained;
- the "Maximum Operational Envelope" within which the aircraft must always remain;
- MET data (need to avoid dangerous areas and to take winds into account);
- compliance with restricted/prohibited airspaces;
- the need to feed the entry gate for final approach at the nominal rate for the time considered;

and given comfort rules such as:

- avoid short-duration (open to discussion) change of altitude;
- avoid short-duration velocity changes;
- comply with the hierarchy of flight parameters (e.g. velocity changes precede altitude changes).

### 3.6 Optimisation of departure time (take-off)

The optimization algorithm may take into account aircraft ready for departure (here we consider the earliest take-off time to be allocated when an aircraft is ready to leave the parking gate).

[1] *By type of aircraft we understand a group of aircraft belonging to the same type, with some type of engine and, perhaps, with parameters related to the age of the engines.*

Let us suppose that for each class of aircraft[2] a common agreement is reached between airlines to define penalization coefficients for delays[3]; it could be represented by a table, as previously, for example Table 2.

Then the algorithm will give optimum take-off times which minimize the global penalization over the 30 mn horizon.

### 3.7 Suggestions for optimization

As mentioned above, a flight is composed of several penalization coefficients :

- some concern a part of the flight which lasts a certain time (many minutes) : let us call them $P_i$
- others are "discrete penalization coefficients"; they concern a local modification of the flight such as a level-off during a climb for a few minutes, an anticipation of or a delay in the TOD (in this later case the use of airbrakes will be necessary) : let us call them $P_j$
- some correspond to a local modification of the flight for example, a holding pattern but last a time which may exceed a few minutes and a penalization which involves time should be considered ; let us call these basic penalization coefficients $P_k$
- ultimately, some of the penalization coefficients are *achieved* (the past of the flight up to the present time) and others are only *forecast* (the future of the flight).

| Delay | Penalization coefficient Heavy | Medium | Light |
|---|---|---|---|
| less than $\theta_0$ | 1 | 1 | 1 |
| between $\theta_0$-$\theta_1$ | 1.2 | 1.2 | 1.1 |
| between $\theta_1$-$\theta_2$ | 1.5 | 1.5 | 1.1 |

**Table 2**

The global optimization algorithm should minimize Q:

$$Q=\sum_{\alpha} P_j+\sum_{\alpha} \frac{1}{T_{\alpha}}(P_i\Delta t_{pk}+P_k\Delta t_{kp})$$

where :

- the first sum operates over all the airborne aircraft in the area considered at the time the re-optimization starts; the 2 other sums are attached to each individual flight which may be composed of several "phases".

Note : as said previously, the above expression contains *past* penalizations and *estimated* penalizations (future of the flights; the *past* penalizations enter into Q as known quantities) ;

- $T_\alpha$ is the duration of each flight (again $T_\alpha$ has two components : the past which acts as "initial conditions" and the estimated duration of the flight at the time the re-optimization is performed).

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2 *For a detailed study, it would be necessary to envisage either the type of aircraft, the number of passengers or a combination of both which should be considered for the definition of the penalization coefficients.*

3 *Here again, it would be necessary to envisage at least two cases : a) the aircraft is on schedule (approved by CFMU in Europe) ; b) the plane is late (or ahead of schedule) - in that case penalization coefficients should be smaller than in case a).*

- $(\Delta t_{ph})_{\alpha o}$ is the duration of the *phase* (climb, cruise, descent) to which a penalization $(P_i)_{\alpha o}$ is attached (here for a plane referenced $\alpha_o$) ;

- the last term corresponds to holding patterns; penalization is assumed to be proportional to time (to be discussed); $\Delta t_{hp}$ is the duration of the holding pattern.

Such a quantity Q is non-dimensional; it could be considered as the *penalization* per unit of time attached to each flight.

A tentative approach to global optimization could be roughly stated as follows :

Let $Q_\alpha$ be the penalization coefficient attached to plane $\alpha$ ; $Q_\alpha$ is composed of two terms :

$Q_\alpha{}^P$ : The **past** (P)penalization already encountered by the plane ;
$Q_\alpha{}^E$ : The **estimated** penalization attaching to the flight, resulting from the last optimization sequence.

A global optimization is such that

$$Q = \Sigma_\alpha Q_\alpha$$

is minimum . It leads to 4-D trajectory for each plane.

As we said, whenever an **event** occurs a re-optimization is performed.

Just before the **event** the set of trajectories was optimum. When the **event** occurs it is advisable first to determine the volume in which 4-D trajectories would be concerned. Most of the time it will be found that a limited number of flights in cruise phase in a given volume, or flights in a TMA, must be re-organised, i.e. re-optimized; it is an iteractive process.

This re-optimization could be made in three steps :

1) find

$$\min \left[\Sigma_\alpha Q_\alpha^E\right]$$

in the volume of possible interferences and store a **set of solutions** close to the minimum;

2) compute for each aircraft concerned their $Q_\alpha$, that is to say add the already acquired penalization $Q^P{}_\alpha$;

3) make the final choice among the set of solutions obtained from 1) in order to avoid over penalizations for aircraft; in other words, to smooth the penalizations for the aircraft concerned.

### 3.8 Some comments about optimization methods:

It would be advisable to investigate about the new improvements of the old *linear programming methods*, naimly to look for the possibility of applying the Kalmarkar method (instead of travelling along the polytop and reach the summit of it, Kalmarkar has developed a method in which an algorithm gives the possibility of going directly from any initial conditions to the summit. Time is saved but, it is not clear whether a quasi real time optimization may be achieved or not when applied to the Air Traffic Control over a large region. More generally, currently used methods should be extended to state vector of the order of 1000 (if some hundreds of planes are concerned in the algorithm process), they should be extended to discrete data.

The most popular method, the *gradient method* lead to apparent minimums and the exploration of the criterion evolution in the vicinity of a minimum takes time; an improvement of this basic method, known as the Tabu method reduces the exploration times but even with this method we think that it will be difficult to operate in quasi real-time.

The *simulated annealing method* comes from the similarity in metal processing when the liquid metal gradually crystallizes. It is well known that if the cooling is too fast, the metal (or a chemical product) may crystallize into an "intermediate state" normally less stable than the final state which will certainly be reached if the cooling is made very slowly. The rapidity of cooling is transposed into the size of increments given to parameters. Here again, the overall time seems too long for any processing close to real-time; the main reason lies in the fact that when a minimum is obtained it is necessary to re-start the algorithm from the beginning, with a slight modification of the parameters to escape from this minimum.

A method which differs a little from the previous ones is the *constraint satisfaction problem.* This is a "declarative method" i.e. a method in which it is checked, at each step, that the constraints are satisfied (a tree of possibilities is first established; variables - here velocity, FL, ... - are initialized and for each set of initial values it is checked that all constraints are satisfied). The optimum is reached by steps without any full re-initialization of the variables; computation time seems shorter than in the previous methods; however the concept of minimization of a function is replaced by the concept of "constraint comply satisfaction". This method is studied presently at CERT for a problem of frequencies allocation in a battle field. In addition to non-interfering constraints it is requested that the highest frequency allocated be the smallest as possible. This is a discrete problem.

A fifth group of optimization methods comes up from the *neuronal technics*; the algorithms used are similar to the ones used in the simulated annealing method, but it is easy to parallelize the architecture (a processor with 1024 SIMD processors cost about 150,000 ECUs). This is not a learning machine but an optimization machine; the weighing coefficients are adjusted by the operator and the problem consists in minimizing a function, by adjusting the coefficients of various terms. To apply this method to the problem as suggested here (i.e. to start from the flight envelopes with the iso-penalization contours), the need to reformulate the global penalization function seems unavoidable.

To conclude these comments, let us mention a relatively new method which seems fruitful. It uses *genetic Algorithms*. Though not yet fully explained on a theoretical basis, it has been applied to many problems including Air Traffic Control [See Refs. 2, 3 and 4].

Natural systems are robust and according to Darwin a permanent evolution exists in each family of living bodies (man, animals, plants) to adapt themselves to the environment "at best". Darwin used statistical data; it is the same in the methods using genetic algorithms for ATC, however a major difference should be noted : if a solution leads to non-satisfactionned constraints (separation of 2 planes below specifications) it must be rejected. Below, we give some indications mainly issued from Ref. 4.

A genetic algorithm optimizes in a set of data; the input data must be coded as a sequence of bits. A "utility function", which is, in our language, the penalization function, is used to evaluate the adaptation or the fitness of a sequence of bits (inputs).

The process is developed in steps :

a) first, at least in the general problem, some random sequences of bits are generated as input data;

b) through the "utility function" the adaptation of each sequence is evaluated;

c) each sequence is reproduced according to its fitness. The well adapted sequences are reproduced better than the other. A new set of sequences (input parameters) is composed by these reproduced sequences;

d) a cross-fertilization is made by random choice of pairs of sequences; to do so, some bits of a datum are exchanged with the bits of another datum; the number of bits so exchanged is also a random choice. Sub-sequences of bits are exchanged between the 2 components of a pair of sequences;

e) at last, one bit is mutated (0 becomes 1 or the opposite); the rank of the bit inside the sequence is chosen at random.

The algorithm is replayed by return to b.

No formal proof has been established yet positive but, it works... thanks to many attempts concerning optimization (in Ref. 2 the author - T. Schiex - mentions as attempts : the optimal distribution of gaz in a pipe, *the optimal trajectories of 2 mobiles which initially are potentially in conflict*, the energy function in a neurone network).

It must be kept in mind that global optimization will become a necessity when the traffic doubles, that is to say in 10 to 15 years. By that time the power of computers will be multiplied by a factor of 5 to 10 with regard to the present situation, mainly by a large development of parallelization.

### 3.9 Tentative conclusion about global optimization

In this chapter, we have tried to show that a global optimization giving a minimum penalization for all the aircraft concerned can be achieved *if common agreement is obtained between the airline operators* ; then, on the basis of a single set of penalization coefficients (associated with their altering algorithms) for the various phases of the flight weighted according to the estimated duration of the phases, a global optimization may be effected through a powerful algorithm.

We did not discuss the optimizing algorithm : it is a difficult problem, but many methods exist. We mentioned many sub-problems which have to be solved and then incorporated in the main problem: the optimization process (namely, estimation of the size of the area in which a conflict propagates).

The goal should be the year 2000. The general problem may be split into two steps :

- first step: take a simple case, the connection of two airports by 2 or 3 routes, put all "singularities" on these routes, set arbitrary - but reasonable - penalization coefficients where they have to be applied and test the optimization algorithm for various types of traffic;

- second step: transpose the algorithm to a real route network, for example the one corresponding to North West Europe, and test the algorithms for real traffic demands.

The comparison of the simulation results and what happened in the case of actual traffic will show the saving obtained.

We give some indication of the two steps suggested in the next section.

## 4. SUGGESTIONS FOR A STUDY

### 4.1 Mathematical study of the optimization process (1st step)

A basic simplified network and basic types of traffic (Figure 4) are suggested to start with.

**Routes :**

Main traffic from A to B (A and B are points at the runway thresholds; aircraft are airborne), 3 parallel routes are shown :

- bifurcations or junctions at 8 nm from A or B
- angles : plus or minus 30 d°
- distance between routes 10 nm

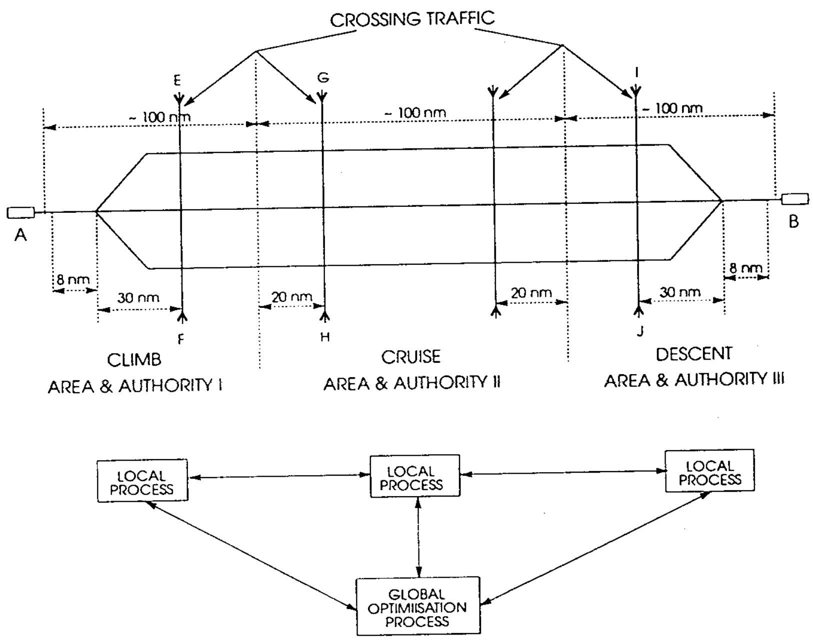


**Figure 4**

**Typical simplified network**

crossing traffic (bi-directional routes and alternate or same altitudes) - characteristics of the crossing traffic:

- CD is performed during the climb;
- EF occurs in cruise but close to the border between the 2 "centres" or "areas" i.e. a few minutes after the border between "authority I" and "authority II". Continuity in the control of the aircraft is requested; "authority I" should have been aware of the conflict possibility except if the conflict could not have been detected before;
- GH is crossing traffic well inside the zone supervised by "authority II";
- IJ is crossing traffic occurring during the descent.

The final objective is to optimize global traffic. However, to begin with it may be looked for optimization of inbound traffic in B.

**Control parameters :**

The ground control (controller aided by computers) may act on the following parameters (not listed in a preferential order) :

1. climb/cruise/descent speeds
2. top of descent
3. cruise level(s)
4. route
5. arrival sequence at B
6. delayed take off at A and at other airports if it is necessary
7. Holding pattern

Note : if necessary and if there is no interference with other traffic, a complete circle (called a 360 degree turn) may be requested. The delay is the requested parameter. The pilot must choose the bank angle in

accordance to delay and the speed of the aircraft. The radius of the circle is then computed and safety rules (separation) should be considered. In any case separation rules should always be satisfied. Circles which correspond to low bank angle (less than 5 degrees) are difficult to control accurately.

**Wind turbulence :**

A 30 kt and 60 degree deviation wind error could be considered, either in the airborne system or in the ground system.

Such errors will be detected by radar plots or by pilot reports with a time-lag lying between 10 to 60 s after stabilisation.

**Traffic categories (traffic mix) :**

Aircraft are divided into 3 classes :

L (Light) : less than 80 passengers
M (Medium) : between 80 and 200 passengers
H (Heavy) : over 200 passengers
T is the maximum take-off weight
T Maximum take-off weight

Cruise speeds and approach speeds, in particular, are difficult to specify in a rough manner; they can be assumed to be as indicated in Table 3.

| Type of aircraft | Cruise M or IAS | Cruise FL | Final Approach (glide slope) IAS (kts) | Landing Speed (kts) | Propulsion |
|---|---|---|---|---|---|
| **H (heavy)** more than 200 passengers | 0.83<br>0.79 | 330 - 370 | 160 | 140 | jet |
| **M (medium)** 80-200 | 0.79<br>0.74 | 300 - 350 | 120 - 130 | 100 - 110 | jet / turboprop. |
| **L (light)** less than 80 | 200 kts | 230 - 270 | 100 - 110 | 90 | turboprop. / jet |

**Table 3**

In a preliminary study the following mixture could be assumed :

in a first stage: all traffic are M
in a second stage : H : 90%
M : 78%
L : 2%

**Traffic densities :**

3 cases could be considered for landing traffic in the final approach capacity of Airport B (traffic densities):

1st case: 25% of maximum capacity
2nd case: 95% constant during a 30 mn period
3rd case: 110% saturation has occurred.

In summary, 18 cases should be considered in a first step ; wind turbulence will be considered later.

### 4.2 Real world, real traffic (2nd step)

Once the algorithms have been tested on a simplified network fed with arbitrary traffic, it will be necessary to check the behaviour of such algorithms on a real network fed with real traffic.

In order to give an idea of the complexity of a real route network, in Chapter 3, Figure 5 shows the route structure of the North West Europe area in which the 5 major cities with their airport or airports are considered.

| | |
|---|---|
| London | Gatewick-Heathrow - City |
| Brussels | Zaventem |
| Amsterdam | Schiphol |
| Frankfort | |
| Paris | Roissy - Orly |

The routes are the interconnecting routes plus the crossing traffic throughout the area.

In Chapter 3, Figure 6 gives the Terminal Area route structure for one airport (Brussels). Aircraft normally enter the Terminal Area at specified points and at a requested altitude. In the case of departure, they normally reach an airport exit point (located within 10

point" located on the main route structure.

Sometimes aircraft are under direct control from Approach Control, they are under full radar control and, thus, they can be guided in "open sky" (vectoring).

Detailed information on dayly traffic is currently available at EUROCONTROL (Statistics Services, Control Flow Management Unit) [Ref. 5]. As an example, documents issued dayly include the following data summarized in a table containing 7 columns.

- countries overflown by the flight (18 binary bits)
- month of the year and the date of the day
- departure airport
- arrival airport
- aircraft type
- nature of flights : military or civilian
- airline identification

## 5. CONCLUSIONS

It is quite evident that, if traffic increases as it is expected, present Air Traffic Management Concept should soon become absolete.

The initial purpose of this paper was to outline the general environment of a RFP (Request for Proposal) aiming at selecting, assessing and running optimization techniques suitable for conducting on-line an efficient management of traffic over Western Europe.

The criteria of the system would cover overall flight economy and maximum use of available capacity En-Route and in Terminals.

Control variables would include individual aircraft flight profiles in both vertical and horizontal planes, whenever possible times of arrival and departure times within acceptable limits.

Full automation is not feasable today but nevertheless it is conceivable and research and experiments have been undertaken in this direction [Ref. 5].

The work that we wish to see undertaken is a natural extension of the concepts presently being implemented with a view to optimize locally the arrival traffic in a Zone of Convergence namely an extended terminal area [Ref. 5].

We think that the next step is global optimization with Controllers in the loop. Any comments about the suggestions made in this paper are welcome.

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# CHAPTER 9

SYSTEMS EVALUATION FACILITIES

# A SIMULATION ENVIRONMENT for PROTO-TYPING AND EVALUATION OF ATM CONCEPTS

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## 1. INTRODUCTION

As existing simulation facilities lacked the level of realism and flexibility to support ATC tool research in an integrated UAC/ACC/TMA Air Traffic Control environment, the STANS facility (Reference 1) has been designed to support the development and demonstration of advanced ATC tools used in the next generation of operational ATC systems. The general structure of STANS allows the quick proto-typing of ATC tools and eases their evaluation in different ATC environments through easily adaptable system characteristics.

In its most condensed form the complete STANS simulation facility is set up on a single desk top workstation, thus bringing the power of an advanced simulation facility to the direct working environment of the ATC system designer without the need of early planning of evaluation exercises. However the systematic application of a client/server architecture ensures that the hardware configuration can be easily adapted to the required extent of the simulation exercises. This provides the capacity for large scale real-time ATC simulations using the same software modules thus enabling a smooth transition from the research environment to pre-operational evaluation.

This wide range of possibilities and the flexibility of the STANS systems will be demonstrated in the section where we describe the experiments/evaluations for which this system has been and is currently used.

## 2. STANS SYSTEM ARCHITECTURE

The STANS system architecture is depicted in Figure 1. Three groups of modules readily identify the "air," the "communication" and the "ground" components.

The basic Air Traffic Control loop starts at the ACCESS (Aircraft Control Console for Experiments, Simulations and Studies) flight simulator. This relays aircraft position and Mode C data to the flight plan data processing system (FPDS). This module supports one or more Controller Working Positions (CWP). Subsequently the air traffic controllers decide on the ATC clearances and relay them through Radio Telephony (R/T) to the "pseudo pilots" who control the ACCESS aircraft in accordingly.

The communications layer has the possibility to simulate any type of data link channel with it's inherent characteristics and limitations in terms of bandwidth and delivery time.

It can easily be configured to investigate what will be uplink and downlink data requirements for potential ATM concepts looking for an increase in controller productivity. This will allow a detailed cost/benefit analysis of the implementation of data link facilities within different airspace and ATC environments.

More interesting certainly, is the possibility to simulate a mix of traffic in terms of airborne and data link equipment levels. This is a basic element as it has now came clear to the people supporting future ATM systems with "distributed" control capabilities in the air and on the ground, linked with digital channels, that the transition phase, where the responsibilities will have to be shared between the ATCO and the computers depending on the level of aircraft equipment, could become so complex that a reduction of capacity will arise and that this will simply invalidate the whole concept. This transition between a totally human centered system and the future system where the computer(s) will perhaps take some decisions under human supervision is a key issue at this moment in time in the world of ATM research.

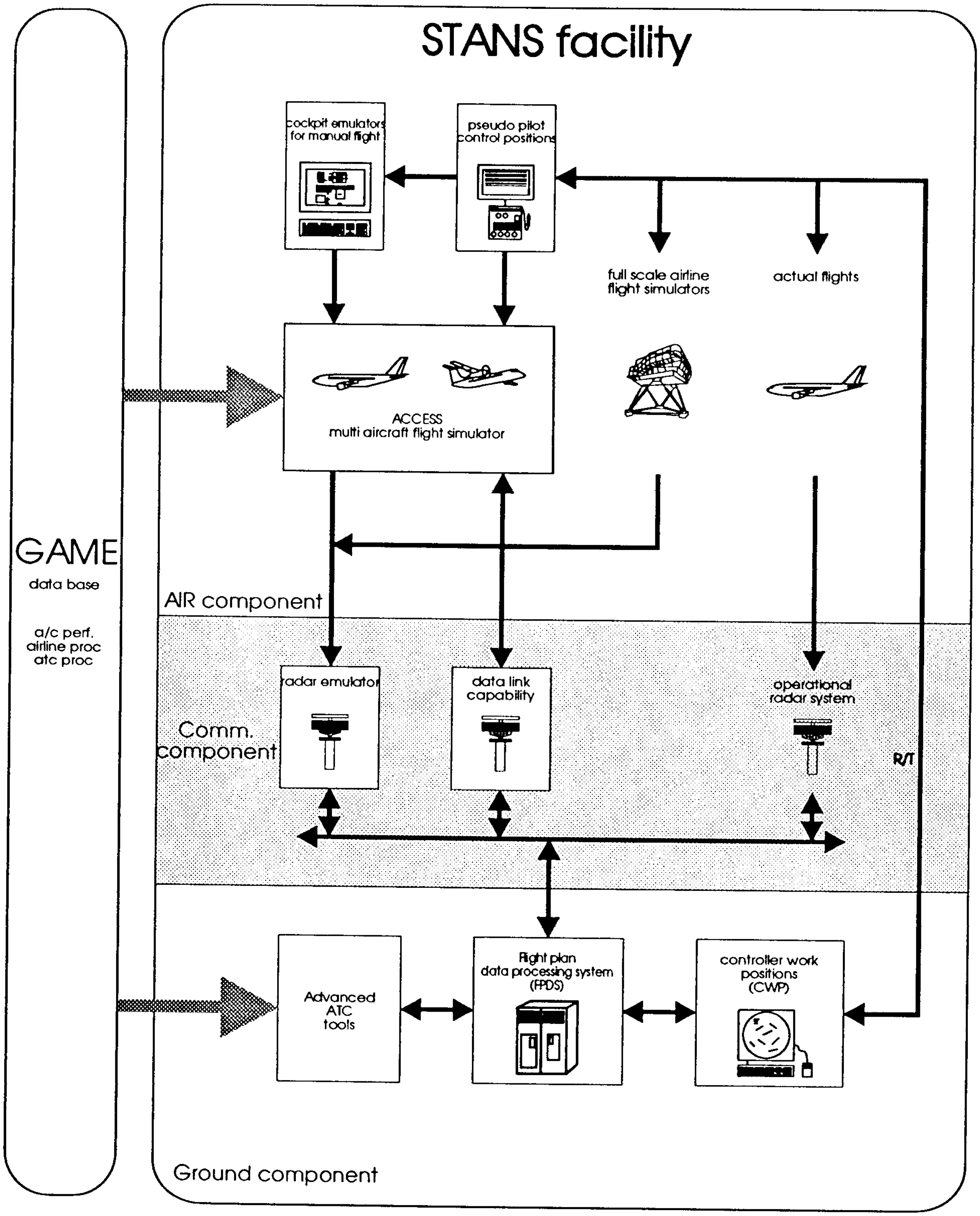


**Figure 1 STANS system architecture**

In the system description shown, the ATM tools modules are completely independent from the basic ATC loop. Such an independent architecture will simplify later on the introduction of such tools into operational ATC systems for pre-operational evaluation and validation.

ATC tools depend heavily on predicted flight profiles and consequently, a complete, coherent data base of aircraft performance models, airline operating procedures and ATC procedures is essential. The GAME (General Aircraft Modelling Environment) data base ensures a high level of consistency between the performance of the air and ground systems and thus provides detailed control of the level of perturbations during evaluation sessions.

This architecture, where the main components are separated and communicate through standard network procedures in a client/server environment, is the base of the system flexibility and portability.

However it should be kept in mind that all these components depend on sets of data provided by the preparation system, which will be explained later, and that such components should always been looked at as a program module and the associated data.

## 3. THE "AIR" COMPONENT OR AIR SERVER

The major "air" component is the ACCESS multi aircraft flight simulator (Reference 2). Figure 2 depicts the general structure. The kernel of ACCESS is a "class B" flight simulator, i.e., the generated flight profiles result from the integration of a simplified set of equations of motion. The algorithms selected (References 3,4) ensure a very realistic aircraft behaviour over the entire flight envelope, from brake release until touch down. More than 500 aircraft can be "flown" in real time from a desktop workstation with realistic aircraft behaviour to the level of thrust setting, flaps and slats operation, etc.

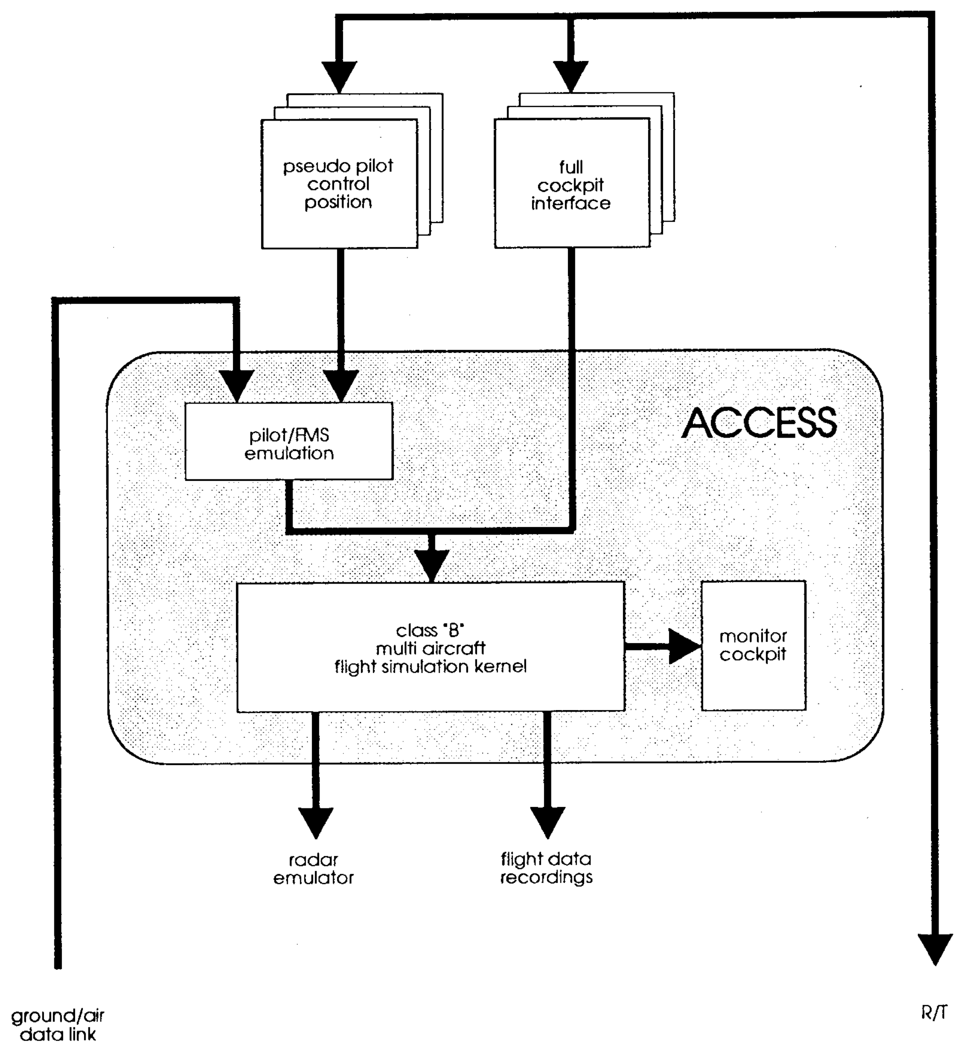


**Figure 2 Components of the "air" system**

For realistic aircraft behaviour, specially in TMAs, the correct modelisation of the aerodynamic aircraft performances (rates of climb/descent acceleration/deceleration) is not enough.

To meet this requirement three control loops, like on real auto-pilots, have been implemented.

The one controlling the roll handles the horizontal navigation with the possibilities of flying heading or radials. The modelisation of the turn performances takes into account the limitation of the maximum bank angle in function of the speed but also considers the transition phase from "flat" to maximum bank angle and back. This quite realistic turning performances gives the possibility to show on the radar screen the influence of a speed change during the turn or the change in shape of the approach ground track because of cross winds.

The one controlling the pitch is used for the control of the vertical evolution of the flight giving the possibilities to fly a specified speed, a specified vertical speed and to capture a target altitude.

The one controlling the throttle is used to fly constant CAS or Mach or to fly manual thrust.

An additional function combining pitch and roll is the autoland function which works like in real airplanes keeping you aligned on the runway centre line and adapting the vertical speed in function of the ground speed to maintain the aircraft on the glide slope.

As explained later on it is possible to fly the aircraft with this control loops as the pilots do but this requires an experienced person per aircraft in flight.

To be able to control a flight at an "higher level" of interaction an Automatic Flight Operating System (AFOS) has been added. AFOS "simply" plays the role of the pilot when he receives a new clearance from ATC or when he has to change the flight profile of the aircraft : first it evaluates the situation and secondly inputs the correct data into the flight director and arms the correct control loops. Obviously in some transition phases or when an instruction conveys more than one clearance (altitude and speed, clear to land) there is a sequence of actions to be implemented depending one on the completion of an other. AFOS takes care of this. Thanks to AFOS it is possible to fly an aircraft with instructions of an ATC type allowing pseudo pilots to fly several aircrafts simultaneously.

With the functionalities described above it is possible for a pseudo pilot to fly several aircrafts simultaneously with a high level of realism. However these version of the ACCESS air system still lacked the possibility of doing forward prediction as the pilot does, thus allowing the pseudo pilot to take the initiative to contact the ATCO for requesting flight conditions closer to the on board computed optimum profile.

This is why a full 3-D Flight Management system functionality associated with a message generator module has been implemented within AFOS. This functionality is required when flights for which no specific ATC constraints exists have to be performed in a realistic way. In particular this is the case for :

- *reduced take-off power* procedure for modern aircrafts in function of the runway length, take-off mass and meteo conditions.
- *optimised V2 speed schedule* procedure which is function of take-off mass, take-off power and runway length.
- *stepped climb cruise* procedure where AFOS will request a higher cruise level if due to fuel burn, the optimum cruise level is considerably different from the current one.
- *procedural ATC constraints*. AFOS can handle a complex series of speed and altitude restrictions in all phases of flight thus allowing adherence to LoA's (Letters of Agreement).
- *vertical profile monitoring*. The progress in the vertical plane is constantly evaluated against *target data* resulting from the optimum flight profile. When constrained by a specific ATC clearance AFOS will issue a request for a new clearance from ATC (like for top of descent). During a flight AFOS can process several *target data* sequentially.
- *energy monitoring*.In AFOS the energy monitoring module controls the operation of the speed brakes which are applied if a forward prediction on the flight profile indicates that a predefined energy state of the aircraft will not be reached with default aircraft operation. The required energy state at a given reference point is defined in terms of target altitude and speed. If due to ATC interventions, an aircraft cannot achieve a stable, predefined state at the decision altitude, AFOS will automatically start an overshoot procedure and inform ATC accordingly.

The functionalities just described allow pseudo pilots to fly several aircrafts on a single position and still have the same behaviour as a profesional pilot in front of the ATCO. This is a key element for realism.

The different possibilities of controlling ACCESS are going to be described in the following paragraph.

Three main interfaces control ACCESS.

The first one provides a full cockpit control interface. Obviously it is the most flexible way to control an ACCESS aircraft but it requires one pilot per simulated aircraft as it has to be able to deal with the auto pilot / auto throttle.
The second interface is through a "pseudo pilot" control position (Reference 5). The operator of this position receives the ATC instructions via R/T and subsequently, enters these through an appropriate Human-Machine Interface (HMI). Depending the ATC environment simulated (TMA or ACC) an operator can handle between 5 and 20 aircraft.
A third interface is provided through a simulated ground/air data link of which the characteristics can be specified. This allows simulation scenarios where controllers can compose ATC clearances on ODID-type HMI's for subsequent transmission to the aircraft the pilot/FMS emulator module converts the ATC directives received through pseudo-pilot control positions or ground/air data link channels into auto-pilot/flight-director/auto-throttle commands. This is a key function for the ATM tools developer as it allows him to immediately check any new change introduced within his software. Note that simulation scenarios are allowed using any combination of available communication channels in parallel (Reference 6).

A further enhancement stems from the advance in multi media support that recently has became available on low cost UNIX work stations. Now voice recognition and synthesis has achieved an acceptable performance level such that, in certain circumstances, it can make the pseudo pilot obsolete. Use of pre-recorded voice data bases offers now the possibility for clearance read back with a voice than can be directly associated to a specific flight.

For each ACCESS aircraft a "cockpit view" can be generated through a "monitor cockpit" process to closely follow pilot activities during the evolution of the simulation. In this window it is possible to have a look in real time in the cockpit of each aircraft to look at the status and changes of all relevant parameters of the flight (e.g. flight director settings and status, configuration, ...) and an additional line is displayed on the top of the screen to monitor messages received from the data link channel or the pseudo pilots positions.

Real time interfaces are provided to integrate several airline flight simulators and/or actual flights into the ATC exercises (Reference 7).

A further section will describe the exercises already performed and the ones planed as well as how external sources of radar data and data link data have been connected and used by the system. This exercices have been organised in order to investigate the potential improvements which can be expected by the ground data processing system with better knowledge of aircraft intentions.

## 4. THE FLIGHT PLAN DATA PROCESSING SYSTEM

In the STANS facility this component controls the flow of information among the various client/server applications subject to the specific simulation scenarios. Interfacing and adapting the STANS FPDS to existing ATC systems is straight forward.

The ATC tools components are using an extended version of the flight plan where all the relevant data for these tools are stored. This data could be used to present to the controller different sets of additional data such that he can decide what will be the data that he can use to increase productivity.
The ATM tools have more knowledge of what will be the plans for the flight as well as what will be the conditions at sectors boundaries as they do a multisector planning of the overall flight. This data, which will be more accurate than the present estimates because it takes into account the whole traffic, will also contribute to give more confidence to the ATCO in the capabilities of the system to plan and organise the traffic across sectors.

## 5. THE ATC TOOLS MODULES

ATC tools will predict in real time, the future evolution of the aircraft based on the available flight plan information, evaluate potential conflicting situations, try to improve the conflict status following a set of strictly defined rules and advise the controller of its findings. The ATC tools will be built from standard modules to ensure consistency. The building blocks implemented at this stage are illustrated in Figure 3 for the ZOC (Zone Of Convergence) Arrival Manager (References 8, 9).

This ATM system is considered to be from the second generation ATM systems as it does not force the aircrafts to follow an early decided plan but as it will be explained more in detail later, it evaluates the traffic situation every time new radar data is available and from there tries to build a plan which will be as close as possible to what the controller would like to see in such circumstances. As the management component is not limited to one sector but extends overall several ones, the system tries to build a consistent and agreed view of the future plan for each flight and will propose the controller to implement it, so reducing the number of interventions which will take place along the whole flight. The intersector coordination is inherent in such approach and will only require minor adjustments from the tactical controllers. Let's now be a little more detailed about the processes taking place in the ATM system.

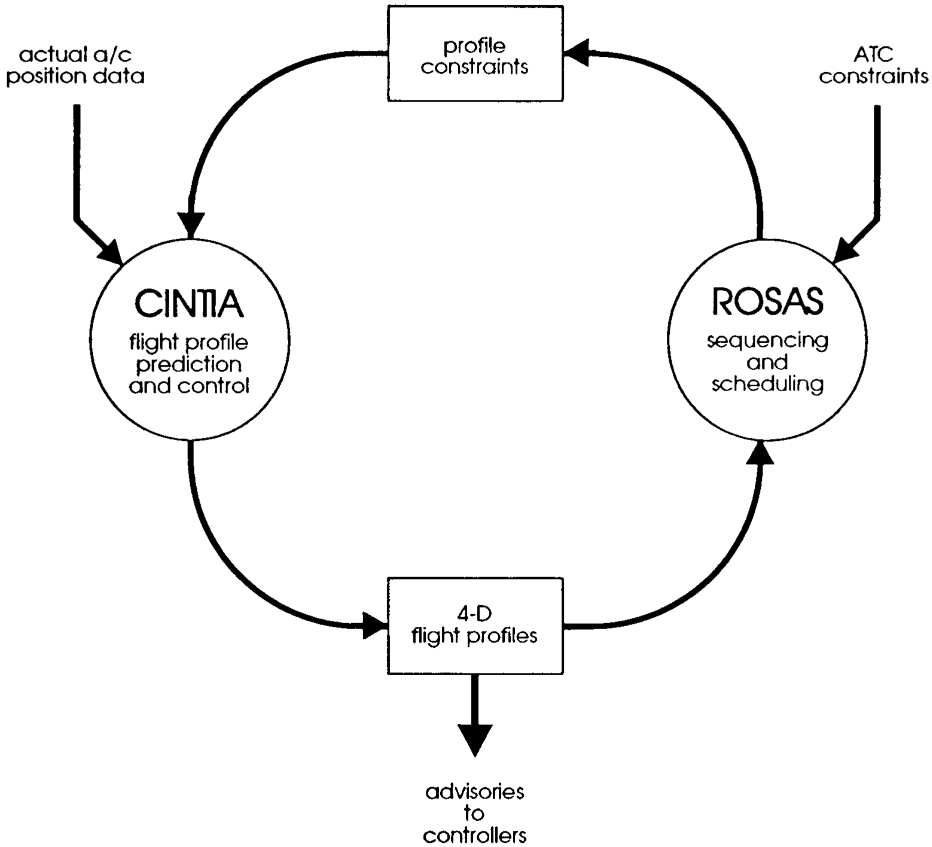


**Figure 3 ZOC arrival manager**

For each aircraft to be considered, the CINTIA (Control of Inbound Trajectories for Individual Aircraft) module predicts a 4-D flight profile based on the observed aircraft position and the current flight plan data. Then the ROSAS (Regionally Optimised Sequencing And Scheduling) module checks the group of computed flight profiles for potential conflicts. If this is the case, a list of "constraints" is compiled for the aircraft involved and subsequently CINTIA will try to compute a profile that meets these constraints. This processing loop continues until the conflict state is acceptable to the ROSAS module. Only then advisories are made available to the controller through an appropriate HMI( Reference 10). To ensure compatibility with the actual evolution of the traffic the above process is repeated every time new radar data is made available to the Flight Plan Data Processing System.

Although the ROSAS logic above is customised for a specific ATM application, the CINTIA approach is much more general and can be easily used in different applications such as Medium Term Conflict Alert (MTCA), etc. Figure 4 shows how CINTIA matches the constraints defined by the ROSAS module. The "TRAJECTORY ENGINE" module computes the 4D flight profile. In effect it "interprets" a kind of "extended" flight plan, called the "SYSTEM PLAN." This system plan is compiled from the GAME data base on the basis of the original flight plan as filed by the airline. To allow a consistent compilation of such a system plan, the data modules in GAME are encoded in a formal "Flight Profile Definition Language", FPDL (Reference 11). The structure of this language is such that, if the computed 4D flight profile does not match the defined constraints, the CONTROL module can update the system plan according to predefined rules.

The trajectory prediction and control functions provided by CINTIA have been validated through many exercises using full scale airline flight simulators manned by airline crews. In these very complex situations the CINTIA algorithms have achieved a typical delivery accuracy of an aircraft at the touch down point in the order of 10 seconds (Reference 12). This compares very favourably with the performance of complex advanced airborne 4D-FMS systems that achieve a 5 seconds delivery window.

The GAME data base layout and possibilities will be explained more in detail within the Simulation Preparation section.

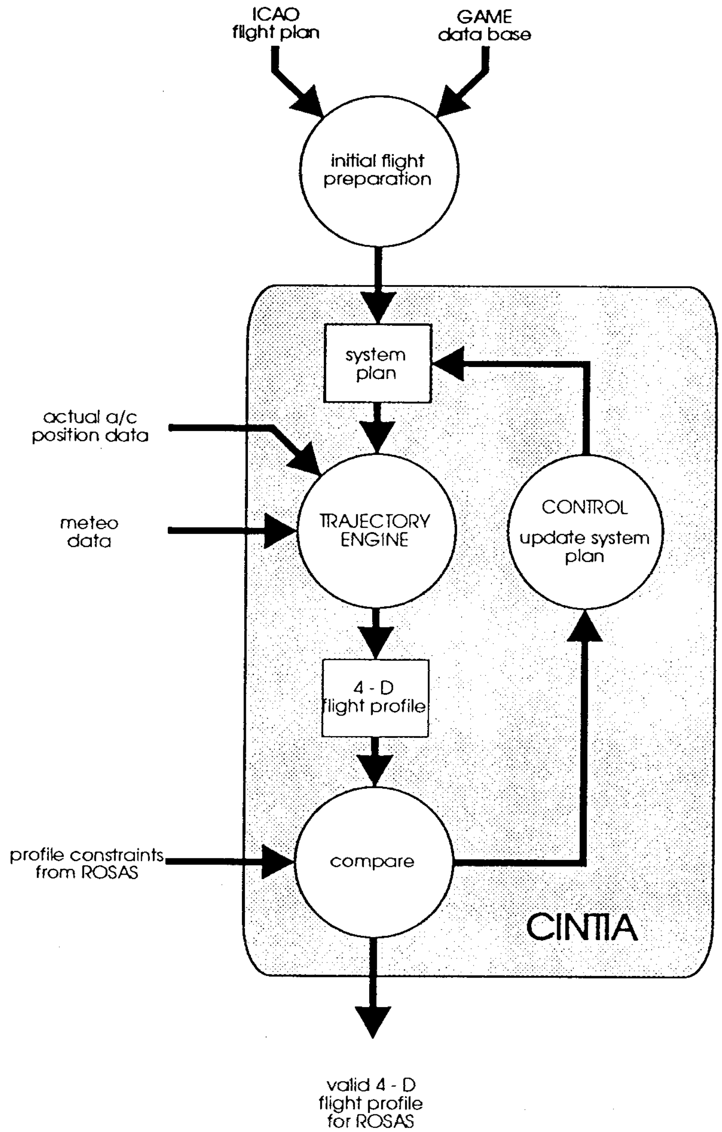


**Figure 4 CINTIA prediction and control**

About the ROSAS arrival manager several comments are to be made. A sophisticated arrival manager should not be based on only a single static criteria for the sequencing activities. This is why, within ROSAS there is a module dedicated to evaluate the present and future traffic situation and the demand for runway slots to decide a shift in sequencing strategies. In low traffic situations the sequencer will try to allocate to each individual flight a landing slot, and so a speed profile, which is as close as possible to what that aircraft operated by that specific airline would like to fly if he will be alone in the sky. However, when traffic increases several other criteria have to be taken into account. Amongst them:

- If several flights have to be delayed because of traffic, the ones in the front of the landing list should be advanced as much as possible in order to minimize the delay accumulated by the following ones and so giving a better global performance.

- If the density of traffic within the TMA increases to a significant level, TMA tactical controllers will require that aircrafts are separated early before the final approach common path in order to make their task possible without a level of stress which could reduce their efficiency.

- To increase runway capacity (a/c landed per unit of time) it is possible to pack the aircrafts per weight categories. This will move the flights away from their theoretical optimum profile but will increase the total capacity.

This is why we consider that dynamic evaluation on the traffic situation is a key component to build a system which reacts in the direction expected by the ATCO and so makes it possible to work together in a more efficient way.

## 6. METEOROLOGICAL CONDITIONS

The architecture allows complete flexibility in terms to access to meteo data servers, i.e., different servers can be provided for "air" and "ground" systems.

Meteo data will be provided in a grid form. The grid layout can be fixed or tailored to the area and the corresponding airways and airports network. The use of different servers for air and ground makes it possible to investigate the level of perturbations introduced by the discrepancy between the meteo experienced by the aircraft and the data on the ground.
As within an ATM system the speed of each individual aircraft is known, this knowledge could be used to improve the ground meteo data by observing the difference between the speed the aircraft should fly and the speed observed by the radar. Such a technique has the advantage of providing the better information where it is the most needed.

The meteo data servers will also incorporate relevant data for trajectory prediction like :

- Turbulence areas where speed has to be reduced
- Icing conditions.

## 7. SIMULATION PREPARATION

To prepare a specific ATC simulation on the STANS facility is straightforward. The definition of the geographical area is easily adapted as it is contained in a few data files. The traffic samples consist of series of flight plans in ICAO format. The simulation preparation system compiles automatically "system plans" from the GAME databases for each flight both for the ACCESS air system and for the ATC tools modules.

The GAME data base provides the relevant data in the following areas:

- Aircraft performances.
- Pilot operating procedures.
- Airline operating procedures.

Figure 5 shows the process of going from the standard ICAO flight plan data to the Extended flight Plan which includes all the data necessary on one side for the air system to realistically fly during the exercise and on the other side to allow the ATM system to build a realistic strategy and compute every time the associated trajectories in a reliable way.

## 8. SIMULATION EVALUATION

The ACCESS air system logs every pilot instruction and provides fuel and flight cost estimates for each flight. Observed radar tracks are recorded by the ground system. A replay facility for individual flights is provided for ATC tool evaluation.

The combination of recording facilities and the possibility of flying the traffic automatically with the up link of the ATM clearances produced by the ground system provides a very suitable system for limited investigation of new management algorithms, of new ATM concepts like air-ground distributed control capabilities or of new trajectory prediction techniques.

## 9. EXERCISES

### 9.1 Large scale simulations

A few years ago a large scale exercise took place at the EUROCONTROL Experimental Centre close to Paris in order to evaluate the concept.

Due to the scope of the exercise and the fact that active controllers have been working with the system it was necessary to use the radar display system of the centre for realism reasons.

On the other hand it was necessary to use the STANS air server to match the level of aircraft behaviour realism, mainly inside the TMA. To match these requirements, the air server of STANS and the ATC tools servers where ported on separated workstations and connected to the EEC simulation computer which task was reduced to drive the displays and run the simulator basic functions like the clock management.

The local preparation system was modified to produce the relevant files needed for the preparation phase and at the end of the exercise the data recorded on the workstations was sent back to the simulation computer for analysis purposes.

Pseudo pilot positions of the STANS system where connected to the air server workstation to allow a maximum of 80 flights being controlled simultaneously. All the connections were made using standard TCP/IP protocols and the Application Programming Interface definition of the servers was made available to the EEC to establish the links.

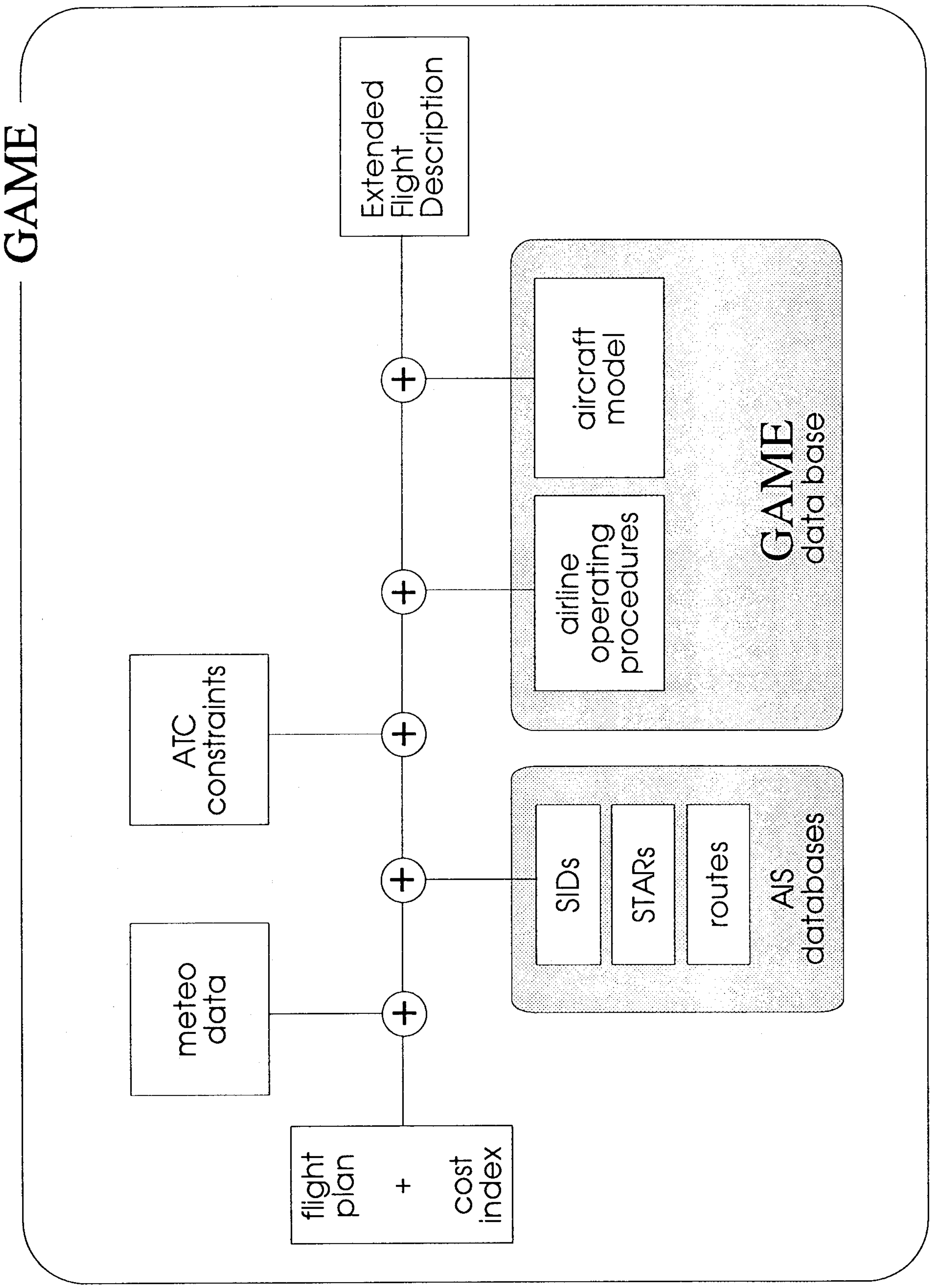


**Figure 5  Preparation data flow**

This exercise has proved the feasibility of doing pre operational evaluation of the ATC tools servers by showing the possibility of connecting such servers in an non intrusive way to an ATC system.

## 9.2 Exercises with airline flight simulators.

Airline flight simulators from British Airways, Finair, Aeroformation and SABENA covering a wide range of aircraft types and manned with full crews have been connected to the STANS system to evaluate its performances in terms of trajectory prediction and flight control.
The most recent exercises with SABENA include a down link of the more relevant aircraft parameters for ground system processing. From these data the ground system can better identify the aircraft intentions and also get the confirmation via autopilot settings that the clearance sent to the aircraft via R/T has been implemented.
The realism of the air server is sufficient to be able to mix the radar data coming from the airline flight simulators ( 3 in the SABENA exercises) and the rest of the traffic simulated by the air server and display it to professional controllers.

## 9.3 Exercises with real aircrafts

In order to evaluate the use of Mode-S data link in future ATC systems an exercise was conducted with the British CAA. The exercise took place at the Defence Research Agency in Bedford, UK, where the BAC-1-11 experimental aircraft of DRA is based. The aircraft is equipped with a Mode-S transponder and full up and down data link capabilities.
The STANS system was used as the ground ATC system with additional aircraft being simulated by the air server.

The Mode-S antenna used was at DRA Malvern, UK and a digital link via telephone line was establish between Malvern and Bedford.

Two types of concepts where evaluated :

- One where only down link data of aircraft performances and meteo information was used to update the ground flight plan processing system.
- One where ATC clearances where up linked and pilot acknowledgements where down linked.

The exercise involve a controller manipulating an experimental HMI of the ODID type and a pseudo pilot in order to fly the additional simulated traffic.

During spring 94, an exercise will take place in Portugal using an experimental CASA 212 turboprop of the Portuguese Air Force to investigate new control procedures to be developed in order to mix slow turboprops in a stream of fast jets within the TMA common path.

The exercise will be a "première" in the field of handling four dimensional control of a real aircraft up to the touch down point in a conventional R/T environment and with the use of data link to partially or totally replace R/T.

The aircraft will be equipped with telemetry and digital data link channel (VHF) in order to perform further investigations in the use of data links.
Other concepts like System Coordination (SYSCO) via the controller HMI will also be investigated.

The STANS system will be configured as a two sector system, one enroute and one approach, and the data coming from the radar and representing the turboprop aircraft will be introduced in the system and mixed with simulated traffic handled by a pseudo pilot.
The figure 6 shows the system setup used for the exercises with the BAC 1-11 and for the trials with the CASA 212.

These quite different exercises show, we think, the flexibility of the STANS system for proto-typing and validation. Also the interface between the components like the ATC tools servers is also relatively easy. This is why we think such a system is an ideal environment for ATM research and proto-typing.

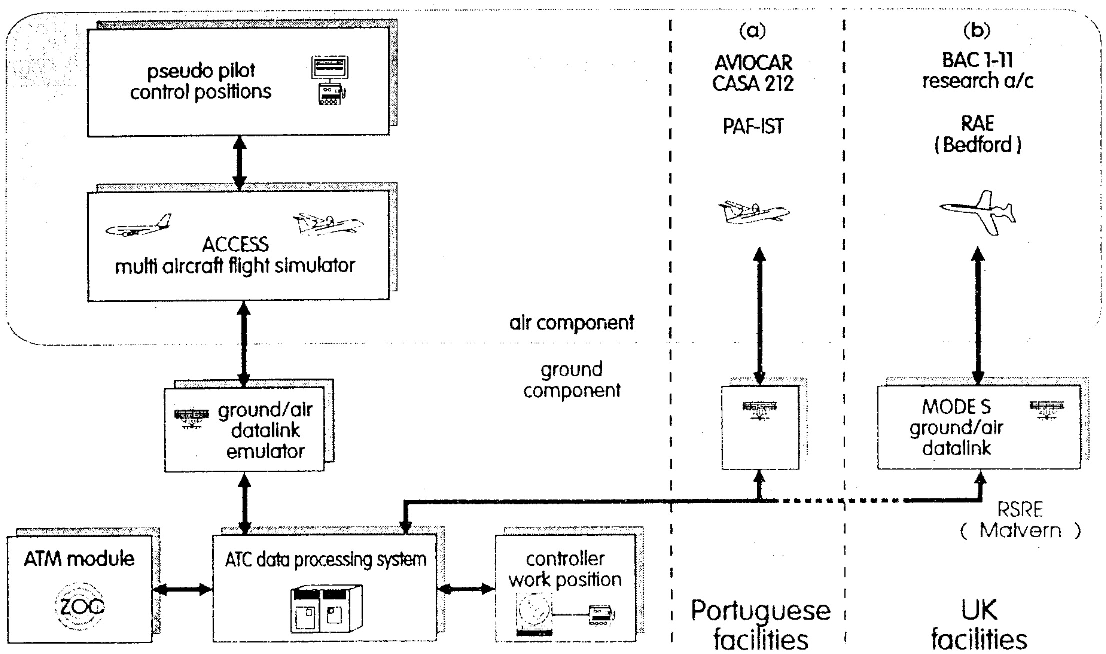


**Figure 6 Integration of real aircraft in R/T and D/L simulations**

**Research aircraft and Mode S**

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# CHAPTER 9

SYSTEMS EVALUATION FACILITIES

# ANNEX

AN ORIGINAL MAN/MACHINE INTERFACE
TO HANDLE MULTI-AIRCRAFT PILOTING IN SIMULATIONS

# AN ORIGINAL MAN/MACHINE INTERFACE TO HANDLE MULTI-AIRCRAFT PILOTING IN SIMULATIONS

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## SUMMARY

In order to satisfy large-scale ATC simulation requirements, a flight simulation facility has been developed by the engineering Directorate of EURO-CONTROL, division E1. The main component is the ACCESS (Aircraft Control Console for Experiments and Simulation Studies) flight Simulator. A description of the initial version is available in EUROCONTROL Doc. 862017, June 86, and an overview of a more recent version is presented in EUROCONTROL Doc. 892010-E, December 89 and in EUROCONTROL Doc. 902013, June 90.

This paper describes another component of this flight simulation facility, viz the SIGMA pseudo-pilot position (System for Input and Generation of Messages for ACCESS).

## INTRODUCTION

### General Setup of an ATC simulation (see figure 1)

The ATC system depicts the general traffic situation and supporting data to the controllers on their working positions.

The controllers send ATC directives via radio telephone communication channels (R/T) to the pseudo pilots who convert them into a form understandable by the flight simulation module. Once per time cycle, the air component through the radar emulator feeds the ATC processing system with new radar.

An additional position, which is not really part of the loop, allows exercise monitoring (displays any information, controls specific simulation parameters, etc...) and on-line analysis.

### The flight simulation module

On a stand-alone basis, without interference from the outside world, the flight simulation module generates 4D aircraft positions on the basis of an aircraft/pilot combination under the assumption that each aircraft is "alone in the sky".

This involves the automatic following of the standard sequence of flight phases such as the take-off following a Standard Instrument Departure (SID) procedure, the following of route from the flight plan information (including the top of descent initialisation) and the approach, localiser interception and landing following a given STAR procedure.

However, the actual progress of a flight is not unconstrained but affected by other traffic in the simulated control area. Accordingly, adequate means must be available to implement ATC directives for each flight concerned. To this effect, interaction with the automatic flight following procedures can be realised in several ways :

- In manual operation, a qualified pilot interprets the ATC directives and implements them through an interface providing the functionality of auto-pilot/flight director/auto-throttle. This approach will produce the most realistic aircraft behaviour, but involves one operator per aircraft. (See Doc. 862017 and Doc. 892010-E).

- To overcome such excessive manpower requirements in large scale ATC simulation, the number of aircraft controlled by an operator should be considerably increased. He/she now becomes a "pseudo-pilot" whose task it is to communicate the ATC directives received to the flight simulation module. In this mode of operation, the flight simulation module has

also to interpret the ATC directives and their logical implementation in the progress of the flight. This involves the evaluation of the directives in view of the flight condition and the subsequent appropriate manipulation of the auto-pilot/flight director/ auto-throttle controls as a real pilot would do.

In particular when the ATC simulation involves traffic in a Terminal manoeuvering Area (TMA), special attention has to be given to the ergonomic aspects ofthe man/machine interface operated by the pseudo-pilot as the frequency and, as a consequence, the total number of messages increase dramatically in these phases of flight.

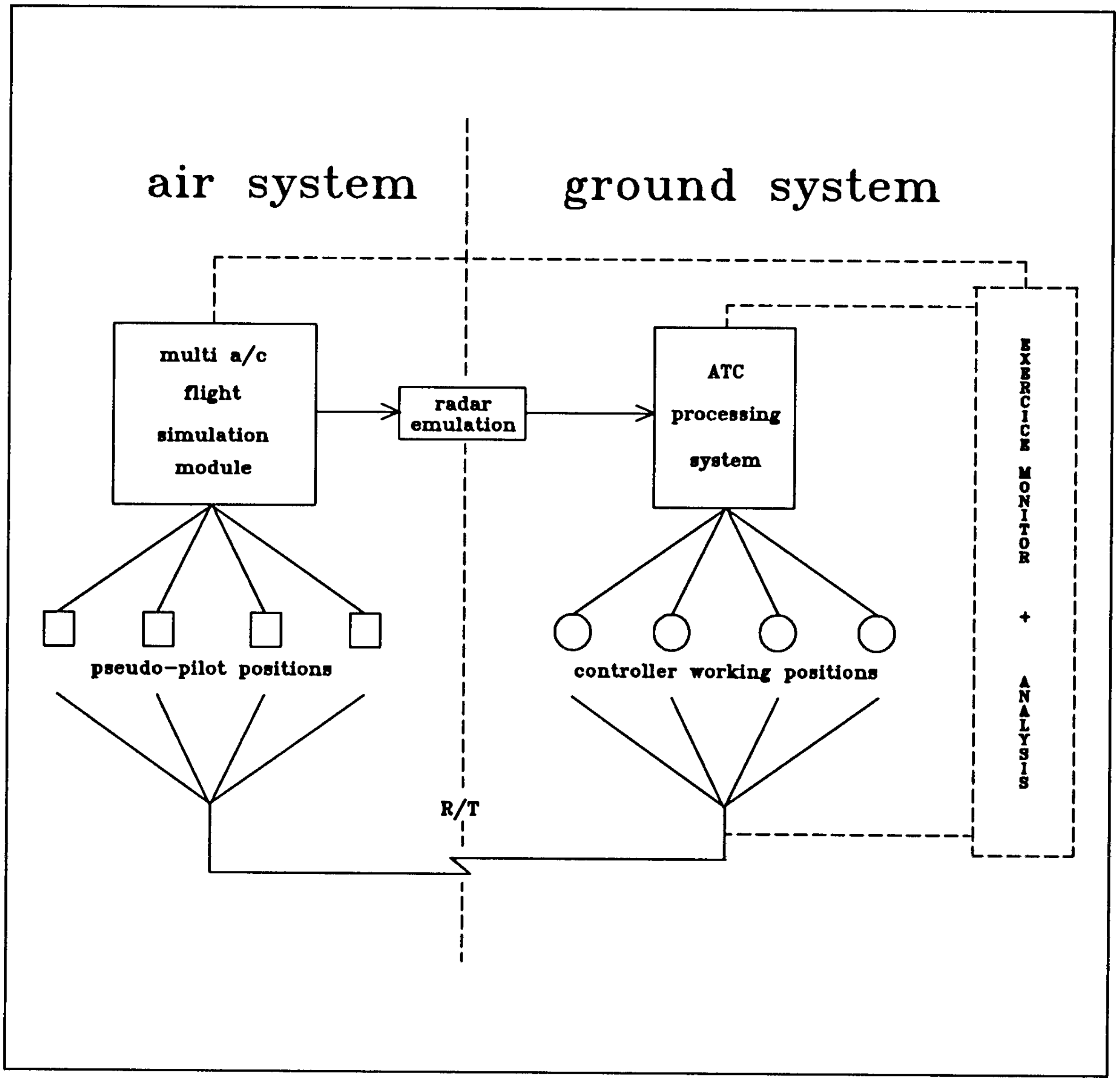


**Figure 1**

**General Setup of an ATC simulation**

## THE SIGMA PSEUDO-PILOT CONTROL POSITIONS

The prime considerations for the design of the pseudo-pilot working positions include:

- to maximise the number of Aircraft handled per pseudo-pilot
- to minimise the potential errors
- to offer a great adaptability to different research requirements.

The SIGMA (System for Input and Generation of Messages for ACCESS) position includes two main components: an input device which consists of a standard off-the-shelve graphical digitizing tablet and the data display sharing the identification of the aircraft presently under control and their flight/message status.

### The input device

A simple digitizing tablet is used to enter the commands : It constitutes a very convenient and ergonomic device.

The large surface available allows the allocation of "selection boxes" for each individual command such that the operator can swifly become familiar with their positions on the board. Commands get activated through a pointing device which does not require great accuracy of operation as the area of the selection boxes can be relatively large.

The advantages of the digitizing tablet are immediatly apparent when comparing it with a "touch sensitive" screen or light pen, mouse, rolling ball or joystick, as these devices require the use of light emitting screen which is considerably more tiring than the passive tablet. In particular, when the size of the screen is such that not all commands can be represented on one screen layout and as a consequence the layout has to be changed through menu selection, the increase in fatigue is considerable due to continual vision adaptation.

The use of the tablet is very ergonomic. Typically the hardware is positioned such that the operator can maintain the normal writing attitude. The training time is minimized as no "menu sequences" have to be remembered and the adaptation of the command layout to specific requirements is straight forward and flexible.

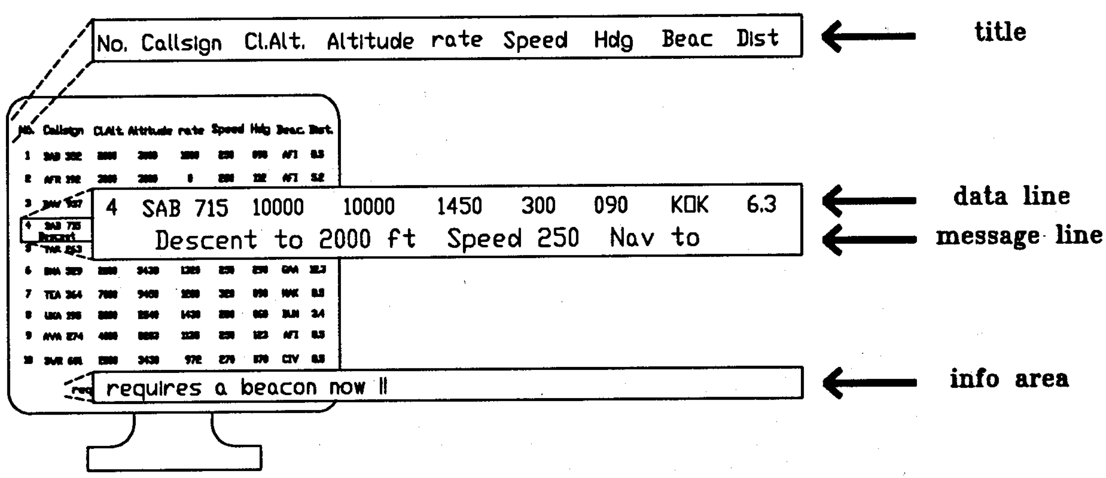


**Figure 2**

**Screen Layout**

### Screen Layout

The other component is the data display (Figure 2). Following the same logic as for the input device, preference has been given to a stable layout, using a single screen/single page to display both the aircraft status and the input commands.

- The position is designed to handle ten aircraft.

Data concerning a particular aircraft is always displayed at the same place (if one aircraft is transferred to another ATC sector, no reordering is operated).

Information for each aircraft is presented on two lines :

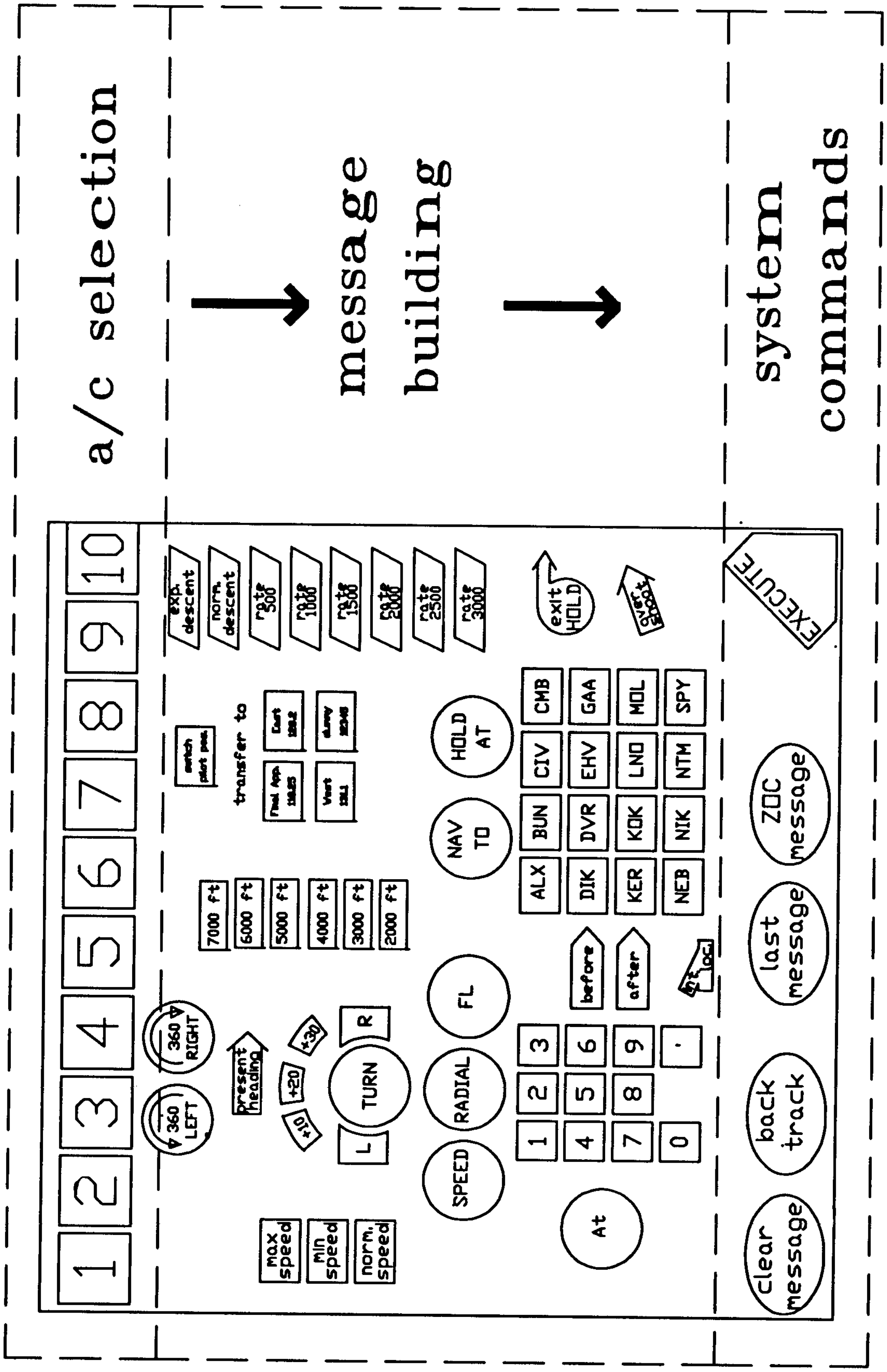


**Figure 3**

**Table Layout**

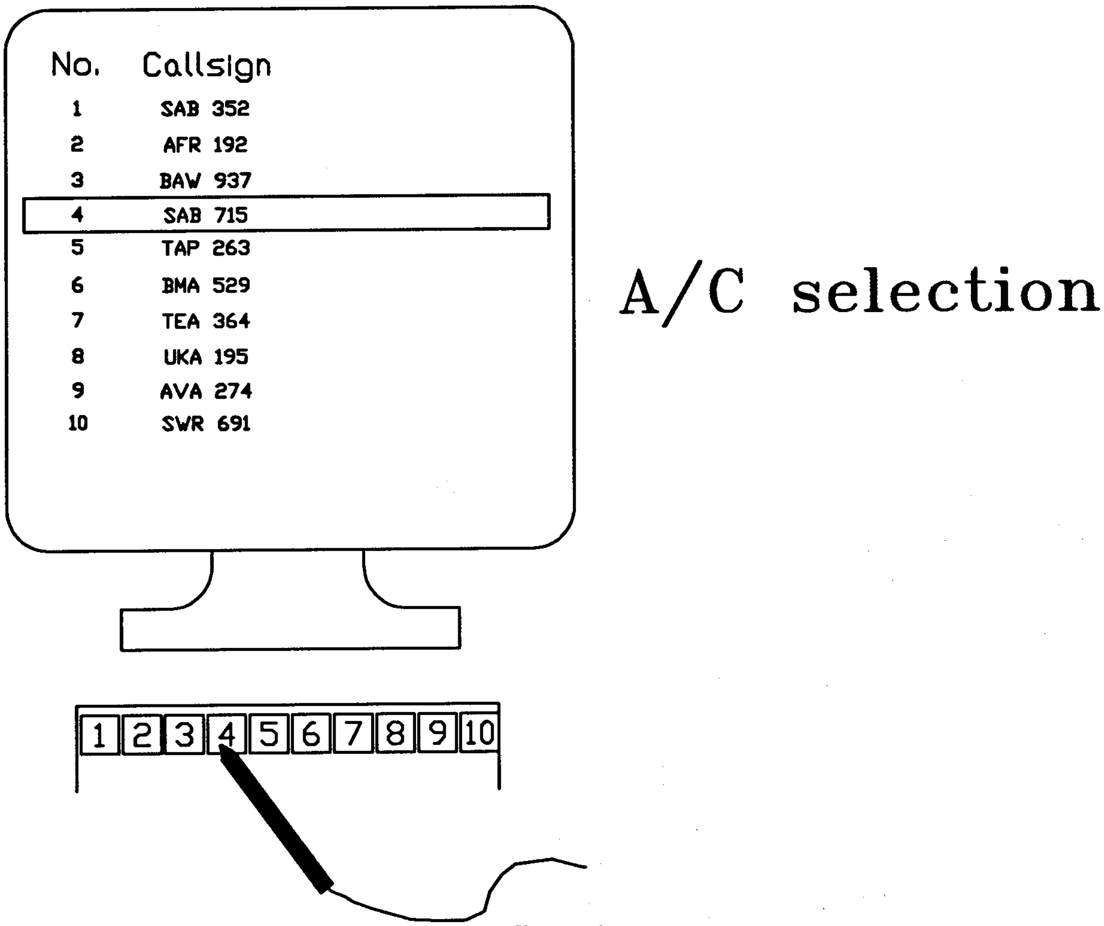


**Figure 4**

The data line gives the aircraft status : altitude, cleared altitude, speed, vertical speed and DME distance to next beacon.

The message line contains a character string corresponding to the selected data areas which follows the common ATC terminology and helps the pseudo-pilot to read the message back.

The info area is used to display error messages concerning syntax errors or values out of range.

Solutions using several screens, several pages on a single screen or pull-down menus have all been rejected. They are slower and much more tiring.

**Tablet Layout**

Typically, the "pseudo-pilot" would receive ATC directives for a given aircraft via an R/T channel. Using the pointing device, he would first select the relevant aircraft, then enter the directive before reading it back to the controller.

Finally the commands entered are sent to the flight simulation module.
The organisation of the tablet layout follows this sequence of actions (Figure 3) :

1) A/C selection

To select a specified aircraft, the operator points to the A/C number corresponding to the callsign displayed on the screen (Figure 4). To simplify this identification, the callsign is split into two parts : the company abbreviation and the 3-digit number.

2) building the command

The complete set of actions can be split into several types (Figures 5) :

- horizontal navigation actions
- altitude clearances
- vertical speed changes
- speed advices
- transfer to other ATC sectors.

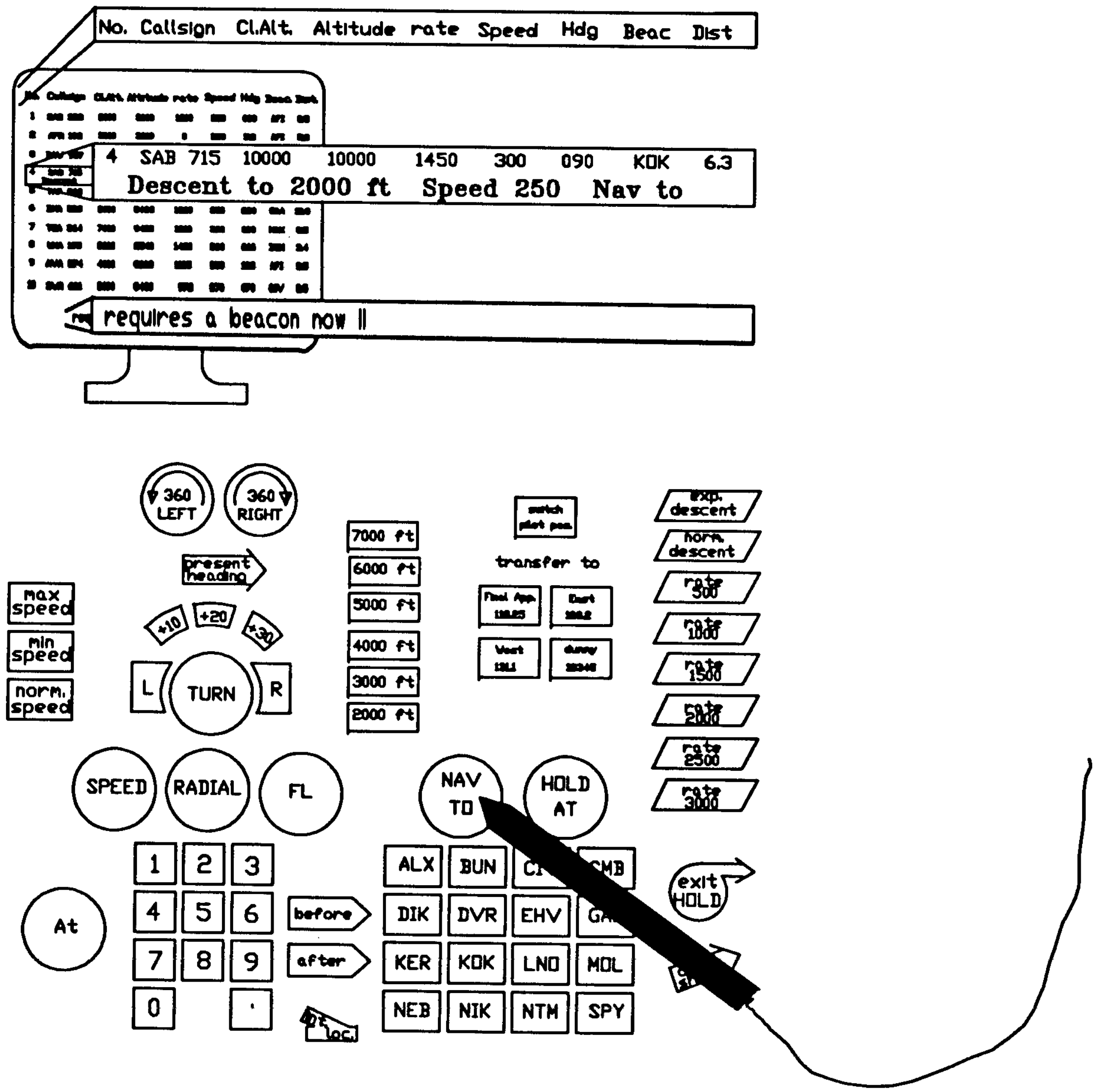


Figure 5

Building the command

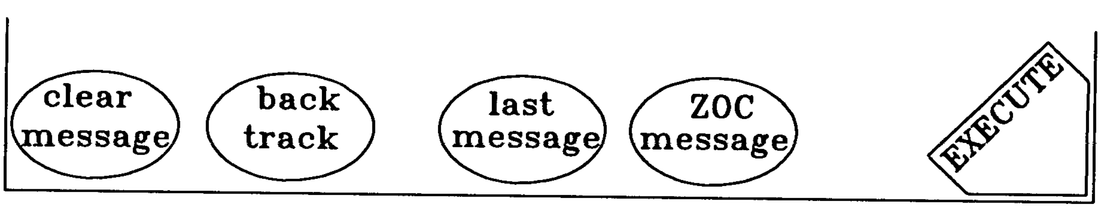


Figure 6

System Commands

In addition, the actions can be combined with a condition expressed as a DME distance to a beacon (for example, "At 5.2 NM before BUN turn right heading 120").

If two actions of the same type are requested (for example "turn to heading 123" and "nav to BUN" are both concerned with horizontal navigation), the latter overwrites the former, as they would otherwise produce contradictory actions.

On the other hand, the order of the selection is not relevant, allowing the pseudo-pilot to enter the commands in the order in which he hears them.

3) System commands

After having built the message and reading it back in the microphone, the operator requests its execution by selecting the EXECUTE cell.

System Commands

Four other editing facilities are available (Figure 6) :

- CLEAR MESSAGE clears the whole message in order to start from scratch
- BACK TRACK allows you to delete the previous input
- LAST MESSAGE displays the previous message concerning this aircraft
- ZOC Message is a special feature used in the ZOC context (see paragraph Applications of SIGMA).

**General Hardware Setup**

The complete setup includes a series of digitizing tablet/low-cost microprocessor sets connected to a mini computer which runs the server software (Figure 7). Basically, the displaying of appropriate data and the editing of the messages is executed by the local processor and the server plays the role of distributor, sending the relevant data to the correct position and collecting the messages from each of the pilot positions to send on to the flight simulator module.

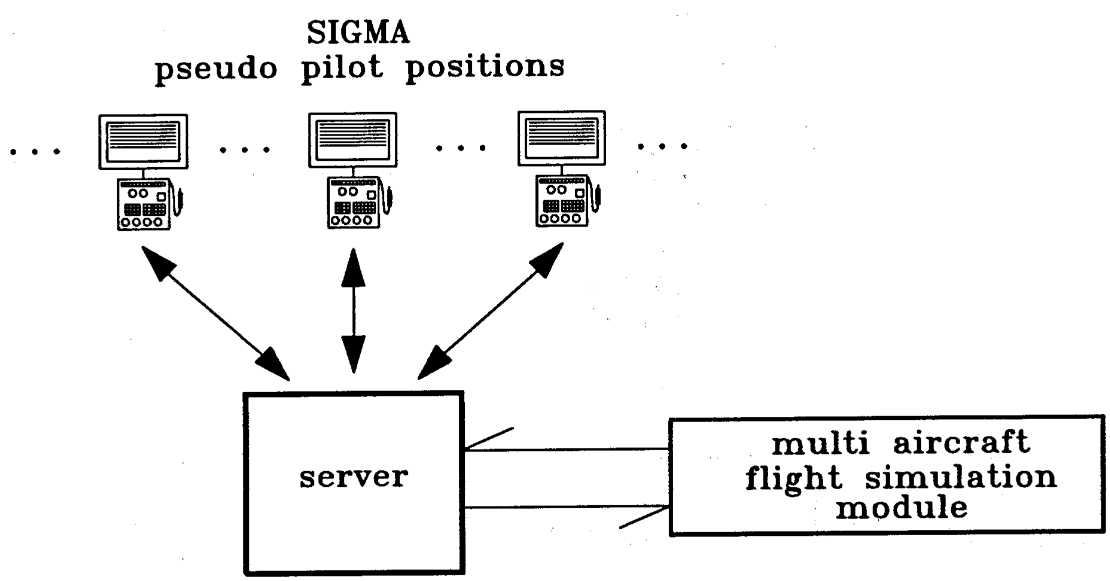


**Figure 7**

**General Hardware Setup**

## APPLICATIONS OF SIGMA

Two different exercise scenarios have already shown the great potential of the SIGMA position.

In the framework of future ATC research, the division E1 of Eurocontrol has, over several years, developed the concept of Zone of Convergence (ZOC). From this research, is born an Air Traffic Management module which advises the controller on how to optimise the traffic stream. It consists of three main modules (Figure 8) :

a sequencer/scheduler, which establishes a landing sequence and associated landing times on the basis of one or more criteria (ROSAS)

a guidance and control module which generates the advisories to achieve the planned sequence (CINTIA)

a main machine interface providing an ergonomic controller/system dialogue.

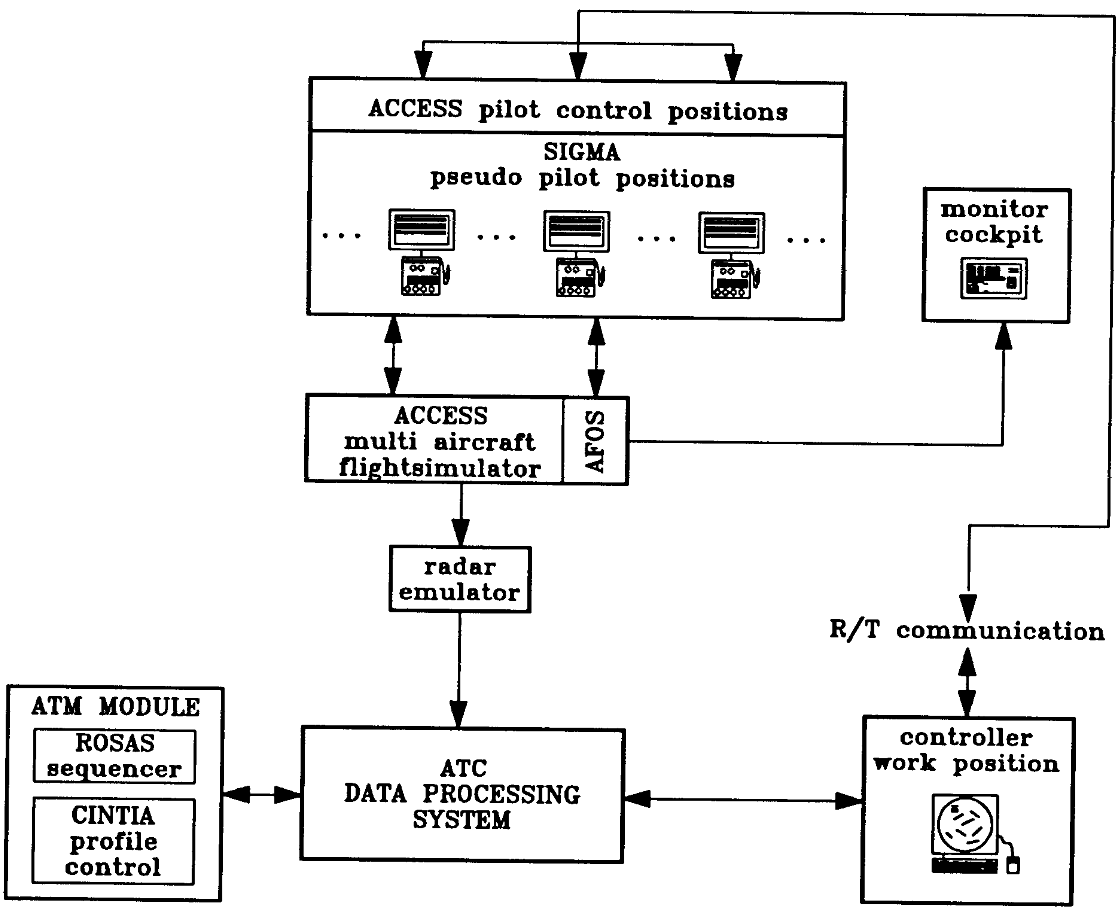


**Figure 8**

**ZOC simulation Setup**

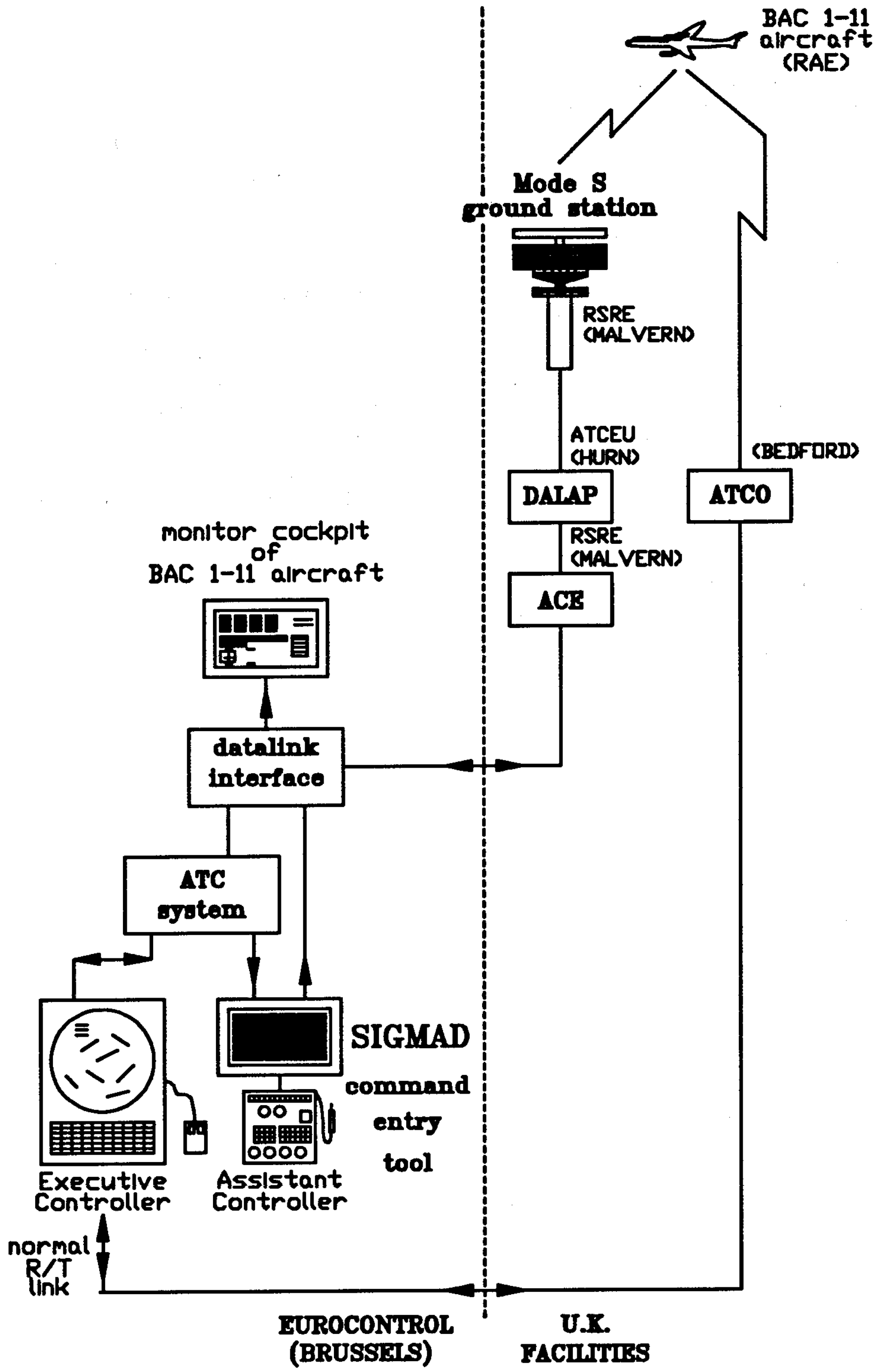


Figure 9

Datalink Exercises Setup

Several simulations have been conducted in order to assess the ZOC concept and in particular a large scale simulation involving qualified controllers has taken place at the Eurocontrol Experimental Centre in Brétigny in June 1989. At this occasion, eight SIGMA positions were used simultaneously to enter the controller directives. In order to simplify the handling of the ZOC specific messages, a special feature has been added to the classical commands : it permits the decoding of the ZOC message in one action, as if the pseudo-pilot had pointed sequentially to the corresponding data selection areas.

The same technique, but applied to a different purpose, has been used in the framework of mode-S datalink applications. One possible application of a ground/air datalink is the sending of ATC directives to the pilot in place of using classical R/T communications. In this case, an interface must be designed in order to provide the controller with access to the datalink channel.

A modified version of SIGMA, named SIGMAD (System for Input and Generation of Messages for Aircraft Datalink) has been developed to this effect (Figure 9).

## CONCLUSIONS

The SIGMA "pseudo-pilot position allows one operator to communicate ATC directives to the flight simulation module for several aircraft, even in cases of simulations involving traffic in a TMA where the workload can be extremely high. It offers a cheap, efficient, easy to learn and flexible command entry tool to satisfy the requirements of large-scale simulations with minimum manpower.

In addition, the concept is an interesting solution to many problems of command input, where speed and accuracy are essential. In opposition to many present software facilities using pull-down menus, one main criterium has steered the design of the command entry position : A passive and stable layout is considerably faster and less tiring than successive screens through menu selection : This has naturally lead to the choice of a digitizing tablet as input device and to a screen layout with fixed location data areas.

# CHAPTER 10

THE AIRPORT OF THE FUTURE

# THE AIRPORT OF THE FUTURE

by

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## 1. "SYSTEM APPROACH" : THE AIRPORT

In chapter 8 we attempted to orient the present study into air traffic control towards a global optimisation concept. We defined the "system" to be optimised over a **wide area** : North West Europe, including 6 major airports. We defined a flight as "from *gate to gate*".

The airport is one component of a wider system, *"the air transportation system"*, the only one considered by the traveller. Moreover, this is the component in which the traveller may learn modifications in the schedules he may have to take decisions, check in and find his way. Once in the aircraft, he is not aware of the kind of flight profiles flown by the aircraft, he is only interested in the duration of the flight (and if he is not a "frequent traveller" he may be anxious prior and during the flight).

This is why the airport must be considered as a major sub-system of the air transporation system and should be optimised (Figure 1).

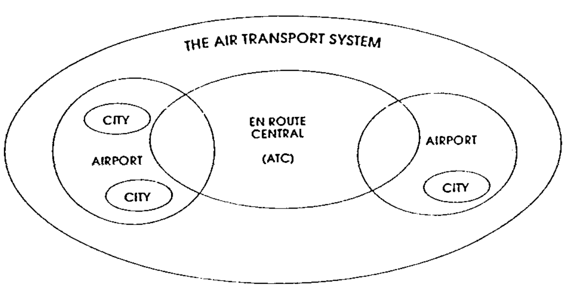


**Figure 1**

**The Air Transportation System**

Let us first define the *boundary* of the system. As we said previously (chapter 6), the flow across the boundary should be measurable.

At the present time, airspace is divided into upper and lower airspace (see Chapter 2, *Airspace partition*). The transition flight level varies according to country, a situation which should be remedied as soon as possible. Within the airspace, aircraft fly along routes plotted from waypoint to waypoint.

When an aircraft arrives in the vicinity (about 100 nm) of the airport at which it is to land, the control of the flight profile passes from the en-route control to the approach control. The boundary between these two controls is not fixed, it depends on the density of the traffic.

Normally the approach rely on the responsibility of the airport, which maintains control until the final approach. Then the tower (TWR) takes over with two different controllers (different frequencies), one for the final approach up to touch-down, one for guidance of the aircraft on the taxiways and aprons. This is obviously an airport reponsibility, effective up to take-off of the aircraft.

Gate operations, aircraft servicing (cleaning, refuelling, catering), all kinds of taxying are the airport's responsibility, as are passenger information, checking in and all kinds of services (food, shops, etc.).

Interconnections between terminals and between airport and town(s) and connections to train networks is the joint responsibility of the airport authorities and the land transport authorities (Figure 2).

Are the flows across this boundary measurable ? Clearly they are. The airflow data are measured at the points at which the transfer from "en-route" to "airport" control is performed. Predetermined waypoints are not necessary. For take-off, the data are related to the departure of an aircraft from its block.

We suggest that the transfer of responsibilities occurs at the beginning of the descent (top of descent TOD), which should be a fixed point on the en-route legs which serve the Airport. The reason will be given in paragraph 3.1.

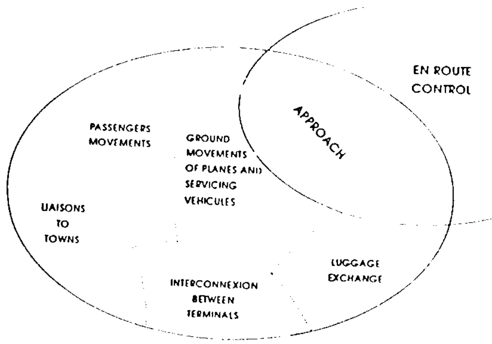


**Figure 2**

**Airport Sub-systems**

Good coordination between the en-route traffic zone and the airport traffic zone in the vicinity of the TMA (Terminal Manoeuvring Area) is a necessity in order to achieve proper global optimisation.

As mentioned in Chapter 8, the type of penalisations encountered in cruise phases and in TMAs either during the climb or the descent are not the same. This is why it is an acceptable trade-off to optimise separately the en- route traffic and the terminal area traffic, sometimes called the traffic in the zone of convergence (ZOC). This is a huge simplification and it is not considered greatly to affect the global penalisation.

In what follows, we will assume that *airport control* starts from the "TOD" in the case of aircraft preparing to land, and from the "level-off" point for aircraft taking off from the airport.

Once the boundary is specified, the *optimisation criterion* or criteria should be defined. In fact the criterion is composed of two different criteria :

- one concerns the minimisation of the in-flight penalisation, as explained in Chapter 8 ;
- the other concerns the quality of the service offered to passengers.

The second criterion obviously includes the delays faced by the passengers. A part of these delays have already been accounted for in the first criterion. We do not intend to specify any "satisfaction criterion" for passengers. We do, however, think that psychology should not be excluded from the definition of this component of "passenger satisfaction" at the airport.

## 2. NEW EVENTS EXPECTED IN THE NEXT 10 YEARS

Global "optimization" of the Airport should incorporate the new technologies which will be developed over the next 10 years, (some of them have been detailed in the previous chapters); they are :

♦ Monopulse SSR with mode S capability. Such radars have the following advantages:

a) they can call aircraft selectively (S)
b) they can carry 56-bit messages (4 such messages can be associated in one long message)
c) the aircraft transponder can also send messages (up to 4x56 bits)
d) however the data link operates only when the aircraft is within the antenna beam. Delays can vary between 2.5 s (two back-to-back antennas rotating at 12 r.p.m.) to 12 s (one antenna rotating at 5 r.p.m.). Such delays should be taken into account with regard to the quality of aircraft guidance.

European coverage (upper and lower airspace) is expected to be completed by 1998/2000, as is US coverage.

♦ The operational use of GPS or the former USSR System; GLONASS (Global Navigation Satellite Systems). Certification of the US GPS system is expected in 1993, but it will not be a full certification as, for example, in the case of ILS/CAT III. The "integrity" of the signals sent by satellites (weather, ephemeris) are not monitored on a permanent basis. Monitoring is effected only when a satellite passes over a monitoring station. Thus a satellite could broadcast incorrect data for 2 hours before notification is given that it has broken down.

Once the CNS (Communication Navigation Surveillance) system is operational, GPS integrity will be achieved (probably around 1995-1997). CNS will also provide navigation facilities with geostationary satellites.

The possibility, for an aircraft or any ground control centre, of knowing the position of an aircraft with an accuracy of about ± 100 m (X and Y) and 150 m (Z) at a rate of up to 1 position per second is an improvement of prime importance.

♦ Monitoring of cleanness of the wing prior to take-off

It seems reasonable to assume that suction of the boundary layer through porous materials will be

operational within the next 10 years. It is nevertheless expected that quick automatic cleaning of the wing prior to take-off will be necessary at least in certain cases.

In winter, when icing is possible, automatic de-icing should be provided by the airport (as is the case at Roissy Airport).

- ♦ High on-board data-storage capacity

In addition to the data which could be stored to monitor the aircraft, it is expected that the storage of one thousand "airport zones", with a 250x250 m grid, will be available on board. The present GPWS will probably be transformed into a much more precise system like Dassault Electronique's G-CAS (Ground - Collision Avoidance System). The airport will be responsible for updating the numerical maps and for modifying procedures. Here again the *integrity* of the data supplied to pilots is a problem entailing safety, and it should therefore be coordinated by a single "authority".

- ♦ High-capacity aircraft (600-800 passengers)

Although designers have claimed that such aircraft will be able to use the current airport structure (taxiways, aprons, etc.), many problems will clearly arise with these new aircraft. They will need at least 3, possibly 4 boarding bridges for embarkation and disembarkation. How would the rear door (or doors) of the aircraft be connected to the airport building ? (the bus system would not seem acceptable, owing to delays).

## 3. A TENTATIVE LIST OF PROBLEMS WHICH ARE THE AIRPORT'S RESPONSIBILITY

### 3.1 Approach (from the TOD on ground-referenced trajectories)

Today the normal procedure is the "idle descent", i.e. from the TOD the pilot chooses a descent IAS (or Mach number), sets the throttle at idle and adjusts the pitch to comply with the selected IAS. This is an "atmosphere-referenced" trajectory. The attitude of the aircraft depends on the local atmosphere characteristics (temperature, pressure, wind, and wind gradient). Ground control has to clear quite a large "tunnel in the sky". It is far from an optimum descent : nothing is optimized at the present time. In the next future it will be necessary to optimize that phase of the flight.

The data to be controlled are :

- the time at which the plane is supposed to fly over a way point (this time is given by the ATC);
- the trajectory with regard to the ground, in order to compensate for winds (and temperature gradients); in order to give the aircraft a ground-referenced trajectory, the ground speed has to be known. Note that the vertical speed is correctly provided by the rate-of-climb indicator; it is known on board.
- the fuel consumed (energy saving) in order to comply with pollution constraints and a reduction of the DOC (Direct Operation Cost).

Thanks to FMS, such an optimization can be achieved now. However, it seems that it is not so much difficult to optimize the descent in a manually controlled flight.

At a meeting held in CERT, Toulouse on May 25 1993, Captain Victor (retired) of American Airlines proved that it is easy to perform such trajectories even when manually controlling the aircraft. Three simulations were performed on an Aerospatiale 321 simulator. The pilot did not know the procedure (he had not attended the meeting which preceded the simulations). The first was a permanent dialogue between Captain Victor and the pilot. The second one was performed by the pilot alone. For the third there was a 40 kt winds and a procedure was followed including a down wind leg. The pilot completed the exercise satisfactorily [Ref. 1].

The benefits for ground control, which is the airport's responsibility in this phase, is obvious.

Detailed studies, simulations and in-flight tests, including high density traffic, should be undertaken.

### 3.2 Detection, tracking of wing vortices

In order to position aircraft correctly and comply with rules governing safety and passenger comfort, it is necessary to know the position of the vortices of all aircraft and their intensity at any point in the sky.

Experiments are being conducted to detect and trace the vortices of aircraft during the take-off phase. It is necessary to extend detection and tracking during the final approach when aircraft are close the minimum separation distance.

### 3.3 Prediction, detection, representation and intensity of local meteorological phenomena

Windshear and downbursts should be predicted before they reach the airport. Correlation of data from different sources, including special instrumentation at the airport, may improve current meteorological forecasting.

### 3.4 Updated database of local meteorological conditions

Thanks to the automatic datalink, which is expected soon, it will be possible to obtain the local atmospheric parameters encountered by an aircraft (data available through INS and GPS). This will be a vast source of actual conditions along the trajectory of the aircraft. In the vicinity of the airport, the large number of aircraft should provide a real-time knowledge of weather data. All the data collected would, however, have to be processed and correlated. The building up of a database, permanently updated, providing the actual weather data in the vicinity of the airport (namely the wind gradients during the final approach) is a difficult task.

### 3.5 Curved approaches in the "final approach phase"

Once the GPS is fully certified (i.e. integrity is achieved) final approaches without a long alignment with the runway (ILS) over 10-15 nm should be studied. The very final trajectory will be the conventional ILS beam, which allows automatic landing, if CAT III certified. Such procedures would take the place of those forecast for MLS. Although X,Y control does not seem difficult, Z control may need careful study. If such procedures are possible - and safe - the flight time within the TMA will be reduced.

### 3.6 Automatic system to control all aircraft ground movements

A system called SAATMAS[1] was described at the IFAC/Intelligent Autonomous Vehicle Workshop, Southampton, in 1993 [Ref. 2].

The arguments in favour of such a system are :

- pollution from aircraft engines during taxying tremendously reduced
- acoustic nuisance during taxying quasi nul
- ageing of components: engines and brakes (carbon discs), improved
- constraints due to poor visibility (risk of collision) could be ignored
- increase the gate efficiency

In the proposed system, the aircraft is collected by automatic tractors (two coordinated vehicles) once it has left the runway. Once the rendez-vous between the aircraft and the tractors has taken place, the engines are turned off and the aircraft is conveyed automatically to its destination parking by at the gate the engine of one of the tractors. The same system controls the transfer of the aircraft from the parking to the runway entry point.

All vehicles operating on the airport runways or aprons are driven automatically or manually but with instruments (cross pointer type) giving instructions to the driver.

Aircraft and vehicles are controlled by a central computer located at the airport. The positions of tractors and vehicles come from two, or three, completely independent systems :

- a differential GPS system
- a navigation system using passive identified beacons.
- a navigation checking system using burried passive beacon

### 3.7 Automatic baggage control for transit passengers

It seems reasonable to assume that only the standardised identification of each item of baggage, at least at airline level, will allow the correct transfer of baggage from one aircraft to another during transits at the airport.

If high-capacity aircraft (600-800 pax) arrive on the scene, the "hub and spokes " concept will work only if automatic switching of baggage is achieved. This will be a complex problem, involving cross-identification of baggage (different airlines), robots to handle the baggage, place it on automatic conveyors, deliver it to the other aircraft, etc.

### 3.8 Icing control/de-icing and wing cleaning for "laminar wings"

This is a study into and the implementation of an integrated structure and the optimisation of the location of such structures at the airport in order to minimise the cost.

Note : certain subjects are not listed here.

### 3.9 Take-off monitor

The above mentioned subjects are directly connected with the Airport; they should be studied as a whole in view of optimizing the Airport sub-system; however some 15 additional subjects are already identified, they

[1] *SAATMAS Système Assurant Tous les Mouvements des Avions au Sol, French Patent n°: 11.*

can be incorporated in this optimization process in order to arrive at a better optimization of the Air Transportation System. To conclude this brief list of subjects to be considered in a global approach, let us mention a last subject : the "take-off monitor". We already have said that the "$V_1$ concept" is a very poor one, it has a correct meaning only in one of sudden engine failure during the acceleration on the runway. For aircrafts equipped with INS, the safe way is to compare, at each instant, the time acceleration (known on board) and the nominal acceleration which should be stored in the FMS; this nominal acceleration takes into account the mass of the aircraft, the slope (if any) of the runway and the MET condition at each instant during the take-off phase. A possible solution would be equipped the runway with a Doppler radar and green/red signals on its border. A ground computer connected to the upgraded MET data base, fed with the mass and balance of the aircraft and to the radars (Dopplers + Distance) will determine if the acceleration is nominal or a real-time basis. No additional equipment are needed on board. (Such equipments have been tested at the French test center at Brétigny a long time ago. New technologies claim for re-opening of the subject).

## 4. CONCLUSIONS

If air traffic increases as expected (4.5% per year), it is hard to imagine how airports can follow this growth rate. By about 2008, traffic will have doubled in volume.

We believe that all problems for which the airport is responsible should be listed and coordinated solutions should be sought. Above, as an example, we gave a list a 9 subjects highly interrelated; they were taken from a list of 24 "technical subjects". It is obvious that many additional subjects related to human behaviour (from town to airport and inside the terminal buildings) should be considered as well; human factors are involved, this is why the problem is a difficult one.

The airport is a major sub-system of the air transportation system. It should therefore be optimised as a whole. This optimisation process should be carried out in line with the global optimisation of air traffic. The boundary conditions could be focused on the airport entry and exit points. At any given time, the en route centre would deliver or accept aircraft at a specified rate at the TMA entry or exit points. At the same time, the airport would accept aircraft at a given rate (entry points) and deliver aircraft at a given rate (exit point). If these rates were compatible, overall optimisation would be achieved. Failing this, compromises should be sought in order to achieve the next best solution.

A global approach of the Airport as defined above (including the TMA), is undertaken by FEDESPACE[2] since October 1992. In the preliminary studies engaged today the interrelationships between the subjects appear to be the dominant factor both for the efficiency of the Airport and the additional cost which will result from a global approach.

The theme of the 7th Symposium on Air and Space safety (Mars 1995) of The Académie Nationale de l'Air et de l'Espace[3] will be "The Airport of the Future including the airspace around it".

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[2] **"SAATMAS : Fully Automatic Tractors for Planes"**
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[2] *FEDESPACE : 1, Avenue Camille Flammarion, 31500 Toulouse, France. (Fax (33) 61263756)*

[3] *ANAE : 1, Avenue Camille Flammarion, 31500 Toulouse, France. (Fax : as above)*

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**14. Abstract**


Following a summary of the activities of the Guidance and Control Panel of AGARD in the field of Air Traffic Handling, this volume constitutes essentially an introduction for those new to the Air Traffic Control Research and Development community, offering, on the one hand, a broad view of the present situation and actual limitations and, on the other hand, some precise idea of a long term system objective.

It is composed of a preface, a general introduction and ten chapters, each constituting an introduction to the corresponding topics, successively entitled:

– The Air Transport System
– Air Traffic Complexity
– Traffic Evolution
– Electronic Aids to Controllers
– Arrivals Management Systems
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– A Look Further into the Future
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